GRAND RIVER BASIN
WATER MANAGEMENT STUDY
TECHNICAL REPORT SERIES

AQUATIC PLANT MODEL-DERIVATION AND APPLICATION

Prepared for the Grand River Implementation Committee

TECHNICAL REPORT No. 14

Ontario

GRAND RIVER IMPLEMENTATION COMMITTEE

3GV

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REPORT # 14

AQUATIC PLANT MODEL - DERIVATION AND APPLICATION

Prepared for the Grand River Implementation Committee by:

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November, 1982
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FOREWORD

The report "Aquatic Plant Model - Derivation and Application" is one of a series of technical documents prepared for the Grand River Basin Water Management Study. The project described herein was undertaken through the Grand River Study Team at the request of the Grand River Implementation Committee.

The material contained in these reports is primarily technical support information and, in itself, does not necessarily constitute policy or management priorities. Interpretation and evaluation of the data and findings, in most cases, cannot be based solely on this one report but should be analyzed in light of other reports produced within the comprehensive framework of the overall study. Questions with respect to the contents of this report should be directed to the Co-ordinator of the Grand River Study, Water Resources Branch, Ministry of the Environment, 135 St. Clair Avenue West, Toronto.

CREDITS AND ACKNOWLEDGEMENTS

The writers wish to acknowledge the efforts of L. Wong and staff of the Limnology and Toxicity Section of MOE's Water Resources Branch who initiated many of the data collection and analysis programs which were utilized during the model derivation phase of the project.

Field data collection and subsequent analysis were carried out over several years by staff of the Limnology Unit and River Systems Unit of the Ministry of the Environment Water Resources Branch. The writers wish to express their appreciation to staff of the West-Central Region of the Ministry of the Environment and the Grand River Conservation Authority for the technical advice and assistance provided during the field surveys.

Thanks are also due to Ms. I. K. Morgensterns and Dr. T. P. H. Gowda for their constructive criticism in the preparation of this report.

DISCLAIMER

Reference to equipment, brand names or suppliers in this publication is not to be interpreted as an endorsement of that product or supplier by the authors or the Ministry of the Environment.

TABLE OF CONTENTS

		Page
SUMMARY		xi
1.	INTRODUCTION	1
2.	LITERATURE REVIEW	2
	2.1 Existing Stream Productivity Models	2
	2.2 Radiation Effects	5
	2.3 Temperature Effects	12
	2.4 Oxygen Concentration Effects	21
	2.5 Nutrient Requirements	21
	2.6 Hydraulic Conditions	24
3.	METHODS	25
	3.1 Introduction	25
	3.2 Field Data Collection	26
	3.2.1 General Description	26
	3.2.2 Hydraulics	26
	3.2.3 Dissolved Oxygen - Temperature	29
	3.2.4 Biomass Density and Washout	29
	3.2.5 Water Quality	30
	3.2.6 Radiation and Light Extinction	30
	3.2.7 *In situ* Respiration	31
	3.3 Laboratory Methods	32
	3.4 Data Analysis	32
4.	MODEL DEVELOPMENT AND DISCUSSION	33
	4.1 Light Submodel	33
	4.1.1 Extinction in Water	33
	4.1.2 Photosynthetically Available Radiation (PAR)	36
	4.1.3 Theoretical Radiation and Back Reflection	36
	4.1.4 Radiation Model	38
	4.1.5 Self Shading	38
	4.2 Temperature Submodel	41
	4.2.1 Laboratory Respiration Studies	41
	4.2.2 Productivity	45
	4.2.3 Washout and Death	47

TABLE OF CONTENTS (continued)

	Page
4.3 Nutrient Submodel	48
4.4 Biomass Estimates and Seasonal Trends	50
4.5 Conceptual Model (ECOL1)	55
4.6 Flowchart of ECOL1	59
5. MODEL TESTING	62
5.1 Introduction	62
5.2 Sensitivity Analysis	62
5.3 Calibration	72
5.4 Verification	78
6. APPLICATIONS	80
7. RESULTS AND DISCUSSION	84
REFERENCES	87

LIST OF TABLES

Number		Page
1.	Optimum Light Intensities for Photosynthesis from Literature	14
2.	Optimum Temperature and Maximum Growth Temperatures	17
3.	Physical Characteristics of Study Reach	28

LIST OF FIGURES

Number		Page
1.	Relationship between Net Oxygen Exchange and Subsurface Light Intensity	4
2.	Relationship between Net Oxygen Balance and Weed Population Density	4
3.	Solar Flux versus Wave Length	6
4.	Angle of Incidence versus Surface Reflection	6
5.	Nomograph Relating Depth of Water, Extinction Coefficient and Percent of Surface Light	8
6.	Relative Photosynthesis versus Light Intensity for Four Species of Tree Seedlings	9
7.	Relative Photosynthesis versus Total Daily Radiation for Marine Phytoplankton	9
8.	General Curve Relating Relative Photosynthesis and Light Intensity for Marine Phytoplankton	9
9.	Graphical Model of Incident Irradiance versus Specific Growth Rate of Phytoplankton	10
10.	Daily Relative Photosynthesis versus Light Intensity at Plant Depth	11
11.	Model of Photosynthetic Rate as a Function of Temperature	15
12.	Temperature-Related Growth Response Curves for *Cladophora glomerata*	16

LIST OF FIGURES (continued)

Number		Page
13.	Respiration of a Mixed Stream Plant Community Related to Temperature	20
14.	Study Reach Locations	27
15.	Turbidity versus Ke in Grand River Study Reach	34
16.	Turbidity versus Ke in Speed River Study Reach	35
17.	Radiation Model as a Function of PARD	39
18.	Shade Model versus Plant Densities	40
19.	Oxygen Respiration Rate versus Temperature for Periphyton	42
20.	Oxygen Respiration Rate versus Temperature for *Potamogeton pectinatus*	43
21.	Oxygen Respiration Rate versus Temperature for *Cladophora*	44
22.	Productivity versus Temperature Submodels for Three Plant types	46
23.	Phosphorus Supply and Storage in Plants in the Grand River Study Reach	51
24.	Observed Respiration Rates in the Grand River Study Reach throughout the Summer of 1978	53
25.	Seasonal Biomass Estimates in the Grand River Study Reach	54
26.	Seasonal Biomass Estimates in the Speed River Study Reach	56

LIST OF FIGURES (continued)

Number		Page
27.	Conceptual Version of ECOL1, the Plant Model	57
28.	Sensitivity of Biomass Production to K_I (growth rate at light intensity I)	63
29.	Error Analysis of Sensitivity Analysis with K_I	64
30.	Sensitivity of Biomass Prediction to $\hat{\mu}Cg$ (specific maximum growth rate of Cladophora)	66
31.	Error Analysis of Sensitivity Analysis with $\hat{\mu}Cg$	67
32.	Sensitivity of Biomass Prediction to R(20) (respiration at 20^oC)	68
33.	Error Analysis of Sensitivity Analysis with R(20)	69
34.	Sensivity of Biomass Prediction to θ (constant in temperature correction)	70
35.	Error analysis of Sensitivity Analysis with θ	71
36.	Sensitivity of Biomass Prediction to REQFAC (nutrient efficiency factor)	73
37.	Error Analysis of Sensitivity Analysis with REQFAC	74
38.	Results of Calibration in Biomass Terms	76
39.	Results of Calibration in Oxygen Terms	77
40.	Resultant Biomass Predictions in Verification Test	79

LIST OF FIGURES (continued)

Number		Page
41.	Simulated Biomass Densities in the Grand River Study Reach for Various Management Scenarios	82
42.	Resultant Daily Dissolved Oxygen Distributions from Management Scenarios in the Grand River Study Reach	83

SUMMARY

One of the tasks identified during the Grand River Basin Water Management Study was to quantify the extent of the aquatic plant problems in the Grand River Basin and to evaluate the possible effects of various basin management scenarios upon the growth of plants in the river.

A computer model, the major tool for integrating the many factors included in a complex aquatic ecosystem, was developed and used in this study. This report, report no. 14, describes the development procedure used and the resultant ecological model formulated, ECOL1, during the basin study.

The modelling process involved intensive data collection in selected study reaches in the Grand River Basin. Biomass densities as high as 1000 gm/m^2 dry weight were observed along with diurnal dissolved oxygen fluctuations ranging from 0.0 mg/L to 20 mg/L. The effects of various factors were isolated and sub-models were derived to reflect the observed relationships between temperature, nutrient supply, sunlight, stream velocity, community self-shading, toxic substance inhibition, and the aquatic plant community.

The model was calibrated on a phosphorus limited reach and verified on a nutrient enriched reach with good results. Some typical stream management projects are examined and the results of the simulations in one of the study reaches are discussed.

1. INTRODUCTION

Aquatic plants, in high densities, can seriously disturb a stream's dissolved oxygen regime. As well, mats of dead and decaying plant material frequently float downstream, clogging river structures and reducing the stream's aesthetic appeal. Control of these plants has been a concern in Ontario in recent years as their areal extent is growing and their effects are becoming more obvious and detrimental.

The Ontario Ministry of the Environment (MOE) Water Resources Branch has been studying the problem of nuisance aquatic plants in rivers for several years in an attempt to isolate the relationships between nuisance plant growths and their environment. The ultimate goal of this work has been to provide control plans compatible with the uses of water which would return the streams to a desirable condition.

A computer model, the major tool for integrating the many factors involved in a complex aquatic ecosystem, was developed and used in this study. This report describes the development procedure used and the resulting model formulated for evaluating the effects of a wide variety of stream management plans on the aquatic plant community. The model can be used to estimate short term effects on the stream's water quality which would result from proposed changes.

A prerequisite to the modelling process involved intensive data collection in selected study reaches in the Grand River Basin. Environmental conditions were monitored, stream water quality was routinely determined and the aquatic plant community response was measured. The effects of the various factors were isolated and sub-models were chosen to reflect the observed relationship. Algorithms were developed which would realistically utilize these submodels in terms of their interaction and importance.

Model testing is also discussed in this report. As well, the model's sensitivity to various input parameters is demonstrated. Typical stream management projects are proposed and simulations are conducted using one of the study reaches under the conditions imposed by these projects. Results are discussed. Model limitations and applicability are listed along with recommendations for further model refinement.

2. LITERATURE REVIEW

2.1 Existing Stream Productivity Models

Relatively few models or quantitative accounts have been made of macrophytes in streams. Their importance in the oxygen and nutrient balance of a stream has been recognized by many researchers; however, a major emphasis of these studies has been on stream productivity resulting from the activity of the phytoplanktonic community. Stream productivity models will be presented here regardless of whether or not they deal specifically with attached plants. Some similarities exist in all photosynthetic systems despite the obvious differences among different types of plant communities.

Rutherford (1977) formulated a predictive model to assess the relative impact of three producing communities on the dissolved oxygen (D.O.) regime of a stream. The Waikato River (New Zealand) was the subject of this study and was found to support populations of macrophytes, phytoplankton and periphyton. Rutherford's model operates on a relatively short time scale and biomass is assumed to be constant. Production and uptake of oxygen by plants is affected by solar radiation and temperature. The model tests indicated that macrophytes were relatively unimportant in the oxygen dynamics of the stream. As a result, the submodels dealing with macrophyte metabolism were not rigorously tested. Also, instantaneous radiation was taken as a function of total daily radiation and time of day. The model was not able to reflect short-term radiation fluctuations. The goal of this exercise was the evaluation of the relative importance of various factors contributing to the D.O. budget along the stream.

O'Connor and DiToro's (1970) well-known river model has been used extensively to evaluate the effects of pollutant loads on receiving streams. A photosynthetic compartment is included to reflect diurnal oxygen cycles; it is driven by a sinusoidal curve simulating the shape of the theoretical daily radiation curve. This model also considers biomass to be constant and in this case all plants are lumped into one group. It has been used successfully in less dynamic streams dominated by phytoplanktonic communities but like Rutherford's model, it cannot demonstrate the effects of short term changes in radiation or water quality on the dynamic plant community. Shelton et al. (1968) presented a model similar to that of O'Connor and DiToro in its scope and limitations.

Westlake (1966) developed a graphical model for the photosynthesis (P) and respiration (R) of aquatic plants in streams containing dense growths of Potamogeton pectinatus. By examining the oxygen dynamics for each depth slice in a stream supporting macrophytes he was able to relate P to actual incident radiation at the appropriate depth. He constructed curves of the net oxygen exchange rates versus subsurface light intensity (see Fig. 1) and net oxygen balance versus plant density (see Fig. 2). These curves clearly illustrate the importance of solar radiation, extinction of light in water and biomass density to a stream's oxygen budget.

The U. S. Environmental Protection Agency (EPA) (1975) published a reference manual which contains several ecological submodels useful in a variety of applications. Other river models containing ecological subsections are presented by Krenkel and Novotny (1977) and Water Resources Engineers Inc. (1968). These publications contain informative discussions of ecological modelling techniques but are primarily concerned with traditional steady state BOD modelling with ecological modifications to reflect the effects of phytoplankton.

No models were found in the relevant literature which attempted to simulate biomass. Biomass is generally considered constant and diurnal activity is reflected by an empirical sinusoidal radiation model. These models are essentially modified steady-state models.

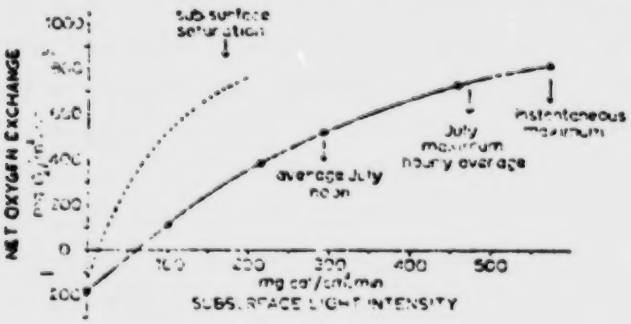


Figure 1: Relationship between net oxygen exchange and subsurface light intensity from Westlake (1966).

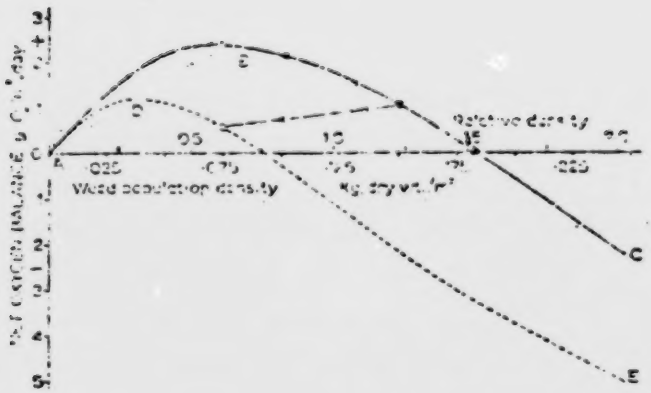


Figure 2: Net oxygen balance versus weed population density from Westlake (1966)

2.2 Radiation Effects

Solar radiation is one of the driving forces in photosynthesis. The biochemical reactions involved are driven by photosynthetically available radiation (PAR) and can be shown to respond quickly to changes either in incident radiation or in transmission quality of overlying water. This section examines incident radiation, extinction of light in water, back reflection at the water surface, the photosynthetically available fraction of the total radiation and the PAR requirements of plants.

Wetzel (1975) illustrates solar flux at the top of earth's atmosphere and at ground level by wavelength (see Fig. 3). It can be seen that incoming radiation is reduced by water vapour and ozone in the visible wave band. Reflection of light at a water surface is a function of the smoothness of the water surface and of the angle of incidence of the sun's rays. That angle is dependant on latitude, time of day, time of year and atmospheric scatter due to atmospheric conditions. Wetzel illustrated the percentage of back reflection that can occur under various atmospheric conditions (Figure 4).

Transmission of radiation in water depends on the nature of the suspended and dissolved constituents of the water column (Wetzel 1975). Shorter wavelengths (green and blue) tend to be scattered and absorbed more rapidly than the yellow and red wavelengths, which partially accounts for the typical blue or green appearance of water. The exponential rate of decrease of light intensity with depth in water is measured by the light extinction coefficient, Ke; Wong et al (1976) suggest the following calculation:

$$Ke = \frac{\ln I_1 - \ln I_2}{z_2 - z_1} \qquad (1)$$

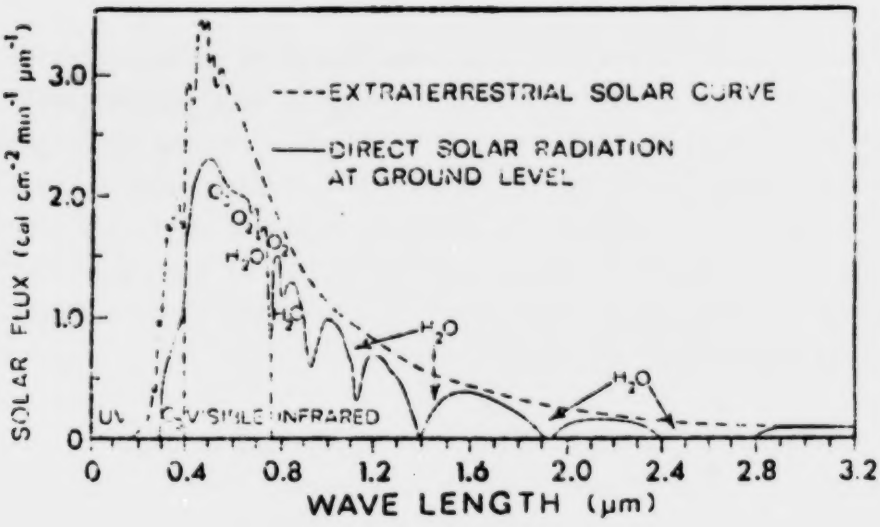


Figure 3: Solar flux versus wavelength from Wetzel (1975)

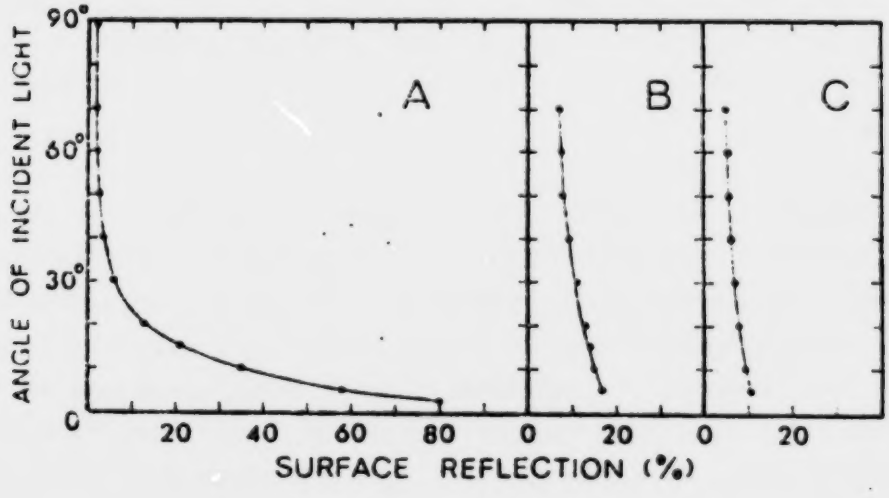


Figure 4: Angle of incidence versus surface reflection from Wetzel (1975)

A - clear, cloudless conditions

B - moderate cloud cover

C - heavily overcast conditions

where I is the light intensity at depth Z. The irradiance at any depth Iz can therefore be calculated as

$$Iz = \frac{Io\ e^{(4.6 - Ke \cdot Z)}}{100.0} \qquad (2)$$

where Io is the light intensity just below the water surface. The nomograph of Figure 5 illustrates this relationship in graphical form.

It is widely accepted that photosynthetic rates will increase as light intensity increases and that at some specific intensity an optimum growth rate will be achieved. If light intensity continues to increase, photoinhibition occurs and the rate of photosynthesis decreases. Daubenmire (1974) observed an increase in the growth rate of terrestrial tree seedlings, reported in terms of relative photosynthesis, P/Pmax, as light intensity increased (Fig. 6). Ryther (1956) observed a similar trend in marine phytoplankton (Fig. 7) and at high intensities photoinhibition was observed. Ryther also related observed total daily radiation to P/Pmax (Fig. 8), demonstrating a trend to an optimum growth rate as light intensity increases. Kiefer and Enns (1976) formulated a model for light-limited metabolism in phytoplanktonic communities. Their model in graphical form is included here in Figure 9. Wong et al (1976) observed a similar relationship between observed P/Pmax and light at plant depth for Cladophora (Fig. 10). While light intensities are measured and reported in various units, thus making comparisons confusing, it is clear that all photosynthetic systems (both terrestrial and aquatic) respond in a similar manner to light intensity.

Several models have been devised to describe this phenomenon. Eppley and Dyer (1965) related growth rate, K, to the mean light intensity $\bar{I}$ in the form of the Beer-Lambert equation,

$$K = Km\ \frac{\bar{I}}{K_I + \bar{I}} \qquad (3)$$

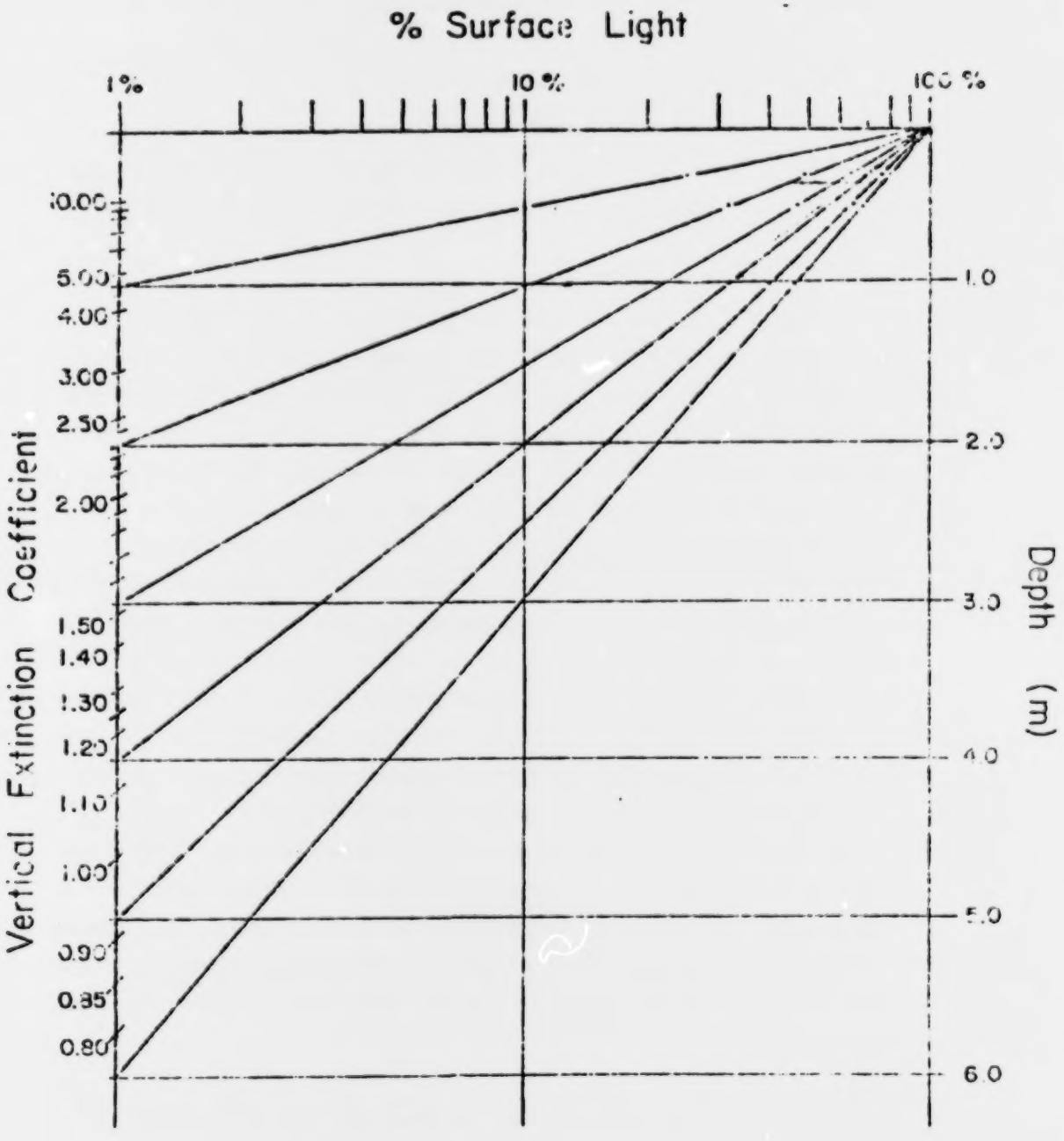


Figure 5: Nomograph showing the relationship between depth, percent surface light and the vertical extinction coefficient.

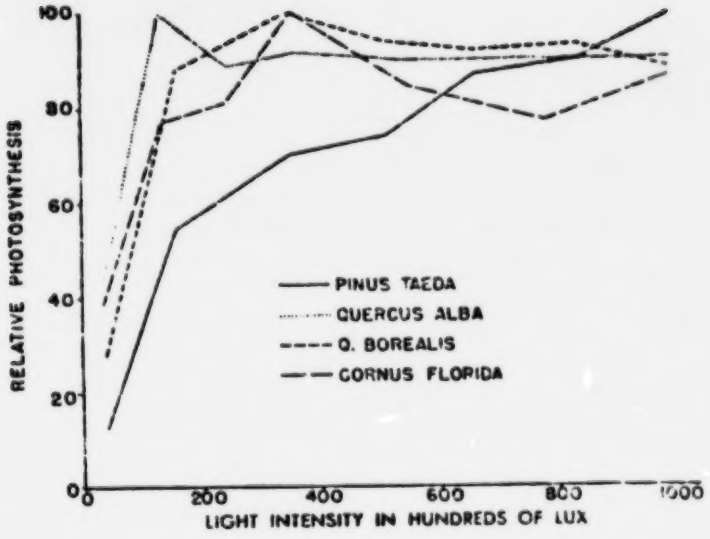


Figure 6: Relative photosynthesis (P/Pmax) of various terrestrial tree seedlings versus light intensity from Daubenmire (1974)

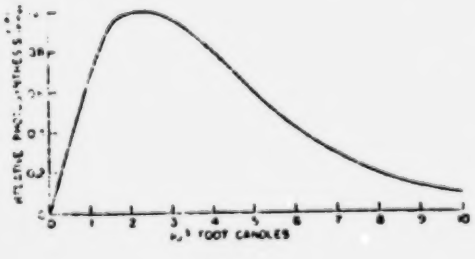


Figure 7: Relative photosynthesis versus total daily radiation for marine phytoplankton from Ryther (1956)

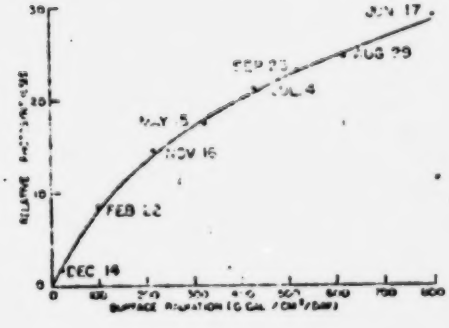


Figure 8: Relative Photosynthesis versus light intensity for marine phytoplankton from Ryther (1956)

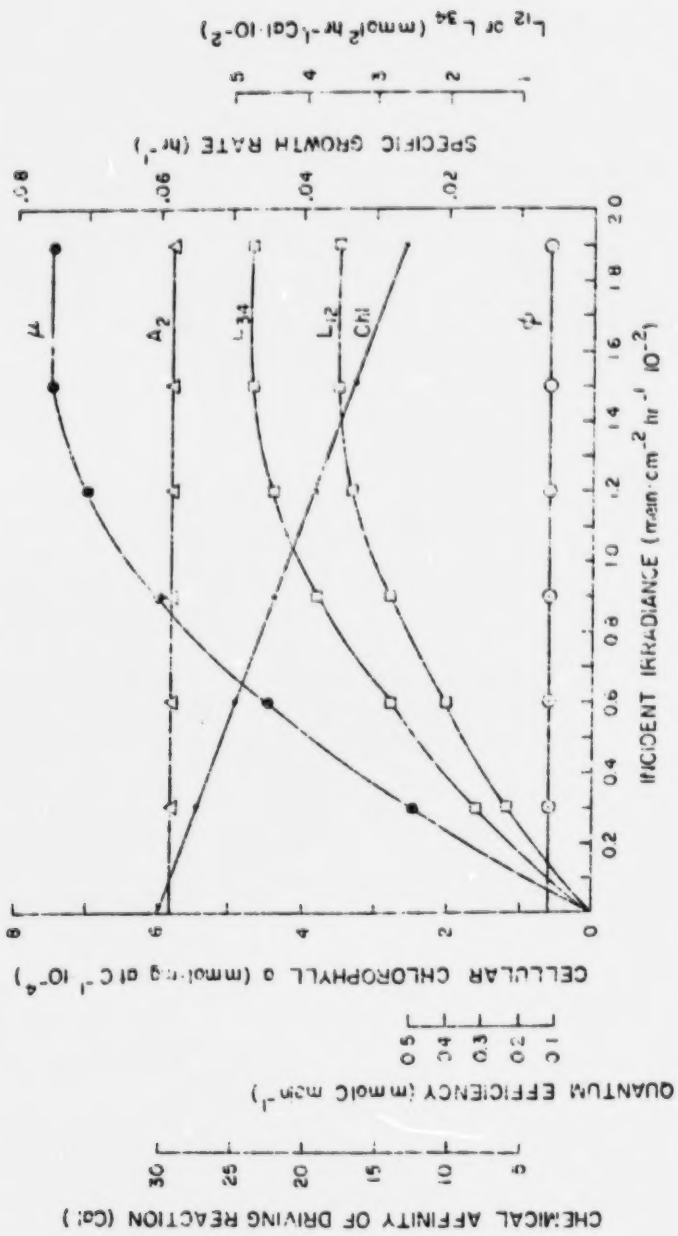


Figure 9: **Model of incident irradiance versus specific growth rate from Kiefer and Enns (1976).**

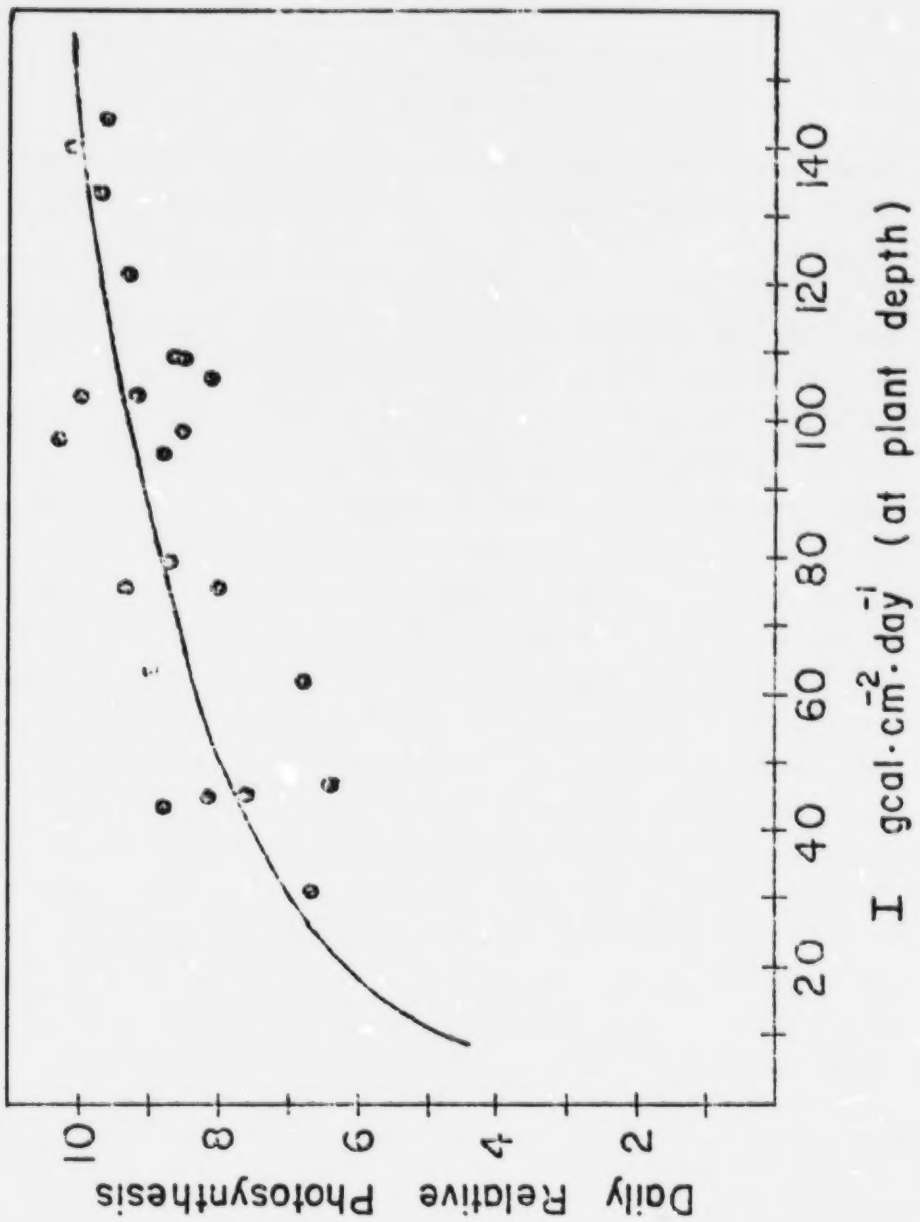


Figure 10: Relationship between daily relative photosynthesis and PAR at the plant depth for Cladophora. Wong et al 1976.

where Km is the specific growth rate and K_I is the intensity at which K = ½Km. Clark and Painter (1978) related P/Pmax to light intensity, I, by the equation,

$$(P/Pmax) = \sqrt{\frac{0.190\ I^2}{1 + 0.190\ I^2}} \qquad (4)$$

These models refine the sinusoidal model used by O'Connor and DiToro (1970), thereby accounting for instantaneous changes in light intensity.

The light intensity at which P/Pmax is optimized varies from species to species, but an order of magnitude estimate can be achieved by examining Figures 6 to 10. These estimates are included in Table 1 and are reported in the same units for clarity. However, the value taken from Wong et al. (1976) is refined to the PARD (PAR at plant depth) while all other values are for total incident visible radiation at the surface of the overlying water (with the exception of the values reported for tree seedlings). While the general response of plant communities to light intensity is similar, this summary of the optimum light intensities indicates that considerable differences exist among species and even among the same types of communities. Measurement of this optimum value is somewhat difficult, since investigators often utilize different techniques for applying light and measuring response; no standard methods exist. Future research should concentrate on measuring specific and universal constants of this type, as that information will lead to further understanding of these complicated systems and enhance ecosystem models.

2.3 Temperature Effects

The productivity of aquatic plants is highly dependant on temperature. Generally plant photosynthetic activity is stimulated by increasing temperatures until water temperature reaches some optimum level. Above this value productivity is less then optimum. At some temperature, well above the optimum, plants will be fatally stressed.

Lassiter and Kearns (1973) proposed a model for growth response to temperature which has been shown to reflect this response for several aquatic plant species. The generalized form of the model appears in Figure 11. In this formulation the shape of the model is characterized by the term 'a' calculated as

$$a = \frac{\ln K_1 - \ln K_2}{(T_1-T_2)+(T_L-T_m) \cdot \ln\left(\frac{T_L-T_1}{T_L-T_2}\right)} \qquad (5)$$

wherein T and K are temperatures and rates respectively at those temperatures estimated from literature, field or laboratory measurement. One must also estimate the optimum temperature for growth (Tm) and the maximum temperature at which growth ceases to occur (TL). The optimum growth rate Km is then calculated by the equation

$$Km = K_1 \cdot e^{-a(T_1-T_m)} \cdot \left(\frac{T_L-T_1}{T_L-T_m}\right)^{-a(T_L-T_m)} \qquad (6)$$

and K(T), the rate at some temperature T is calculated as,

$$K(T) = km\, e^{a(T-T_m)} \cdot \left(\frac{TL-T}{T_L-T_m}\right)^{a(T_L-T_m)} \qquad (7)$$

for $T \leq TL$

$$K(T) = 0 \qquad \text{for } T > T_L \qquad (8)$$

Values for T_m and T_L have been reported in the literature for some species and are highly variable. Storr and Sweeney (1971) observed a growth reponse similar to the temperature curve reproduced in Figure 12. Note that the T_m and T_L values appear to be about 18^o C and 25^oC respectively for Cladophora glomerata.

Table 2 contains approximate values for T_L and T_m reported in the literature for relevant species. As is the case with absolute values of radiation for optimum growth, specific temperature optima are poorly defined. Generally, Cladophora has been found to grow well at temperatures of about 20^oC and does not grow well at temperatures above 25^oC, although exceptions have been observed (Mason (1965), Gerloff and Fitzgerald (1976), McKinley (1978)).

Table 1

OPTIMUM LIGHT INTENSITIES FOR PHOTOSYNTHESIS
FROM LITERATURE

SOURCE	INTENSITY langleys per minute	COMMUNITY AND CONDITIONS
Daubermire (1974)	2.4 inc.*	terrestrial tree seedlings
Keifer and Enns (1976)	4.50 inc.	model for light limited phytoplankton communites
Ryther (1956)	1.8 inc.	marine phyto-plankton
Wong et al (1976)	0.24 plant depth	Cladophora
Whitton (1967)	5.2 inc.	Cladophora
Phinney and McIntire (1965)	7.0 inc.	periphyton

*incident light intensity

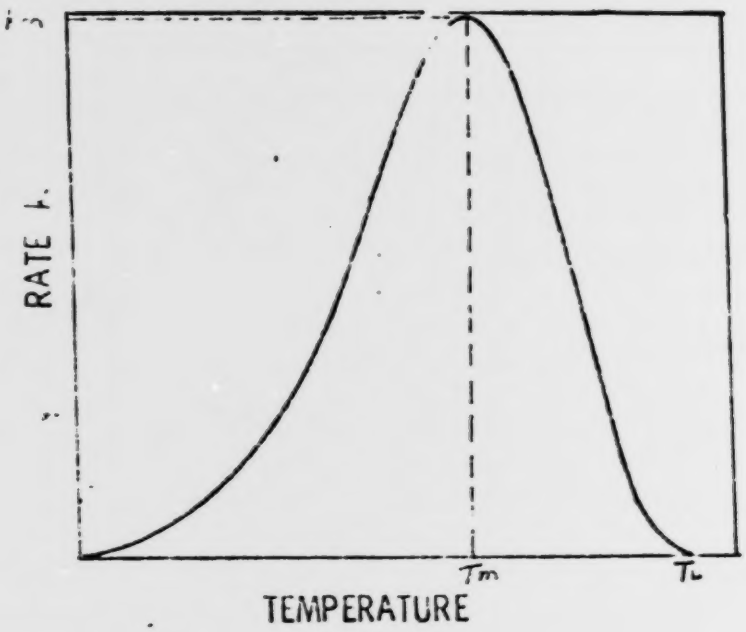
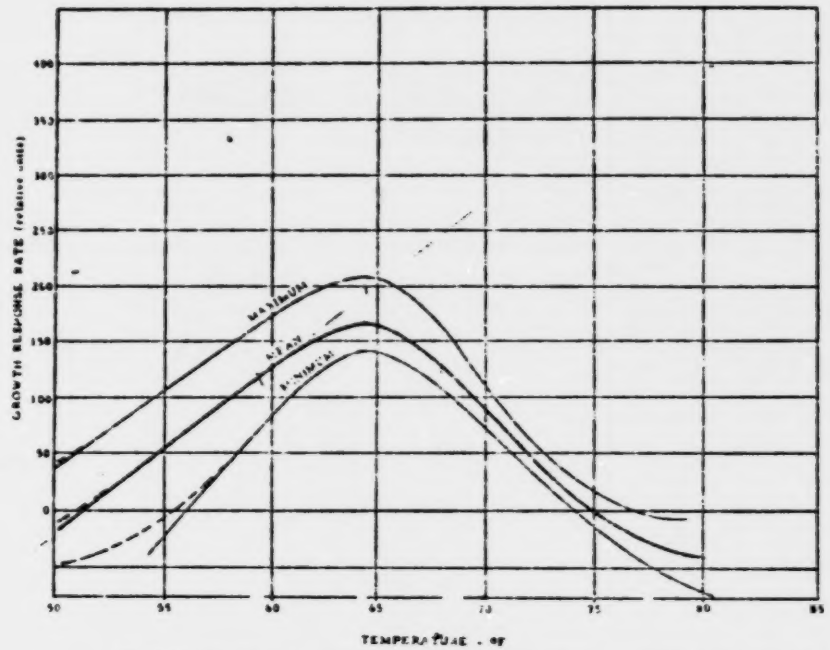
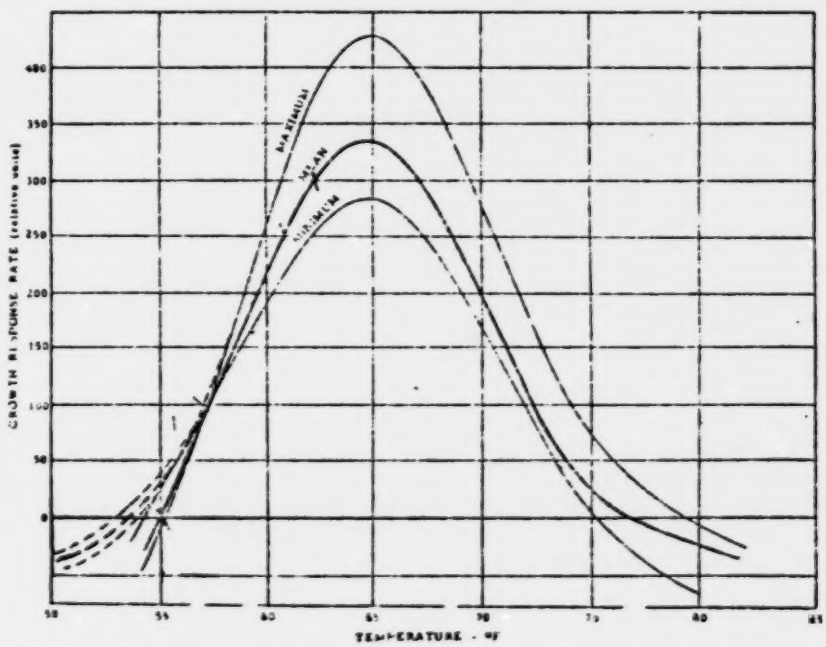


Figure 11: General shape of the graph of biomass productivity versus temperature as described by equations 5 - 8 (see text).



Cladophora growth rate-response to temperature, 12 hr photoperiod-30 days.



Cladophora growth rate-response to temperature, 14 hr photoperiod 30 days.

Figure 12: Temperature related growth response curves of Cladophora glomerata from Storr and Sweeney (1971)

Table 2

Optimum Temperatures Tm and Maximum Growth

Temperatures TL Cited in Literature

SOURCE	Tm	TL	COMMUNITY OF SPECIES
McKinley (1978)	<25°C	>30°C	Cladophora
Neil and Owen (1964)	21°C		Cladophora
Whitton (1967)	15-25°C	30°C	Cladophora
Thurman and Keuhne (1952)		>24°C	Cladophora
Moore (1977)	26°C	33°C	Cladophora
Storr and Sweeney (1971)	18°C	25°C	Cladophora
Saitoh et al. (1970)	30°C		Potamogeton crispus
Wong et al.	>20°C		Potamogeton pectinatus
Blum (1956)		>25°C	Cladophora

Potamogeton pectinatus grows best at higher temperatures (about 25°C) and does not appear to be inhibited by stream temperatures below 30°C. Periphyton communities are composed of various species displaying preferences for various temperatures. As is the case for bacterial communities, the collective optimum of periphyton communities is near or above the highest temperatures achieved in natural aquatic environments.

Aquatic plants respire continuously and this respiration generally increases exponentially as temperatures increase. McDonnell (1971) observed this increase for macrophytes and recorded a Q_{10} for respiration of 2.6. (Note: Q_{10} is a factor defined as the ratio of the reaction rate at a particular temperature to the rate at 10°C lower, in this case the reaction being macrophyte respiration). Owens and Knowles (1969) observed an average Q_{10} of 2.3 for a mixed macrophyte community. Owens and Maris (1964) observed Q_{10}'s ranging from 1.54 to 3.48 for macrophytes in English rivers. A typical curve of community respiration related to temperature from Phinney and McIntire (1965) appears in Figure 13. Similar trends have been observed for mixed periphyton and macrophyte communities as well as pure cultures. The Q_{10} values reported in the literature range from 1.2 to 3.5 when respiration is measured as oxygen consumed.

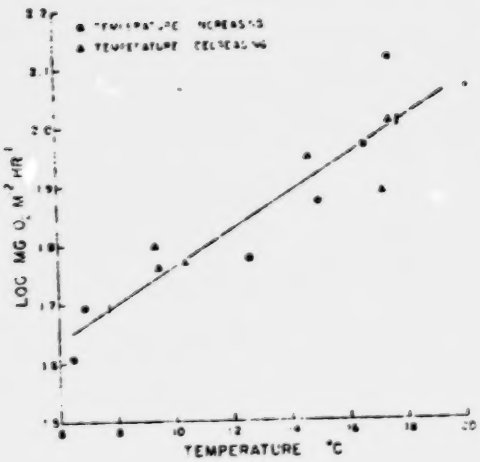


Figure 13: Respiration of a stream plant community versus temperature from Phinney and MacIntire (1965)

2.4 Oxygen Concentration Effects

Several researchers have observed that aquatic plant respiration is dependent to some extent on the availability of oxygen. This fact is particularly important in streams which experience severely depressed DO conditions, or in slow moving water in which significant local oxygen concentration gradients can occur.

McDonnell (1971) studied macrophytes in a stream and observed a positive relationship between DO concentration and respiration of oxygen throughout the DO concentration range, although his data did not extend below 1 mg/L. Similar results were obtained by McDonnell and Weeter (1972). Owen and Maris (1964) also observed the trend with three species of macrophytes; they modelled the relationship with an empirical expression.

$$R = a\, C^{b} \qquad (9)$$

where R is the respiration rate, C is the oxygen concentration of the water and a and b are empirical constants. This type of relationship has been found to be typical for all benthic communities including bacterial and protozoan communities and those also comprised of macroinvertebrate species (Walker and Willson 1981).

2.5 Nutrient Requirements

The growth and respiration of aquatic plants has been simplified in a stoichiometric relationship by McDonnell (1971) as,

$$C_aH_bO_cN_dP_e + (a + \frac{b}{4} + \frac{5}{4}d + \frac{5}{4}e - \frac{c}{2})\ O_2 \ \underset{P}{\overset{R}{\rightleftharpoons}}\ a\ CO_2 +$$

$$(\frac{b}{2} - \frac{d}{2} - \frac{3}{2}e)\ H_2O + dNO_3 + ePO_4 + (d+3e)\ H^+ \qquad (10)$$

While many other minerals are involved in the synthesis of organic matter, the five elements in this equation constitute the majority of cell material. The stoichiometry of organic material is variable, but a typical expression for algae may be given by

$$C_{114}\ H_{196}\ O_{46}\ N_{20}\ P$$

wherein the ratio of phosphorus (P) in biomass would be 0.0123 and nitrogen (N) to P would be 8.75 by weight (Aiba and Ohtake, 1977). Phosphorus and sometimes nitrogen are often the only major nutrients which limit further growth of aquatic plants in aquatic ecosystems (Dillon, 1974; and Vollenweider, 1968).

The quantity of P or N required by plants can be derived from equation 10 and is usually a fixed amount specific to a type of plant or community. However, aquatic plants are not 100% efficient in removing nutrients from surrounding water and many nutrients are in a form which is chemically unavailable for plants. Laboratory experiments are usually carried out to observe the growth of aquatic plant communities under various concentrations and forms of nutrients, in order to determine the minimum concentration of each nutrient required for optimum growth. Many environmental variables (solar radiation, velocity, temperature, pH, etc.) complicate this type of analysis but this approach has led to the acceptance of guidelines of phosphorus concentration for quiescent and flowing waters (Ontario Ministry of the Environment, 1978). While much research of this type has been conducted on benthic environments, very little has been done in lotic environments such as is the case in this study.

Several studies have concluded that excessive nutrients are responsible for an overabundance of Cladophora (Hawkes, 1964, Neil and Owen, 1964 and Jackson, 1966). No reference was found in the literature to naturally occurring Cladophora populations limited by the availability of nitrogen.

Painter et al. (1976) observed that relative photosynthesis (P/P max) of Cladophora in the Grand River decreased when phosphorus contained in plants was less than 2.0 mg/gm. It was also found that plants could maintain this level of stored phosphorus when total phosphorus in water was about 0.06 mg/L. These trends were similar for Potamogeton pectinatus; that this species did not grow in significant quantities when ambient P concentration was below 0.03 mg/L. No relationships were found between nitrogen in plant tissue and nitrogen in water; however nitrogen concentrations were greater than 0.9 mg/L (as N). The lowest P/N was about 26. This value is far above the critical ratio (8.75), indicating that N was not observed at a limiting concentration in this system. In this study, phosphorus in plant tissue was observed to be as high as 6 mg/gm for Cladophora and 4.1 mg/gm for P. pectinatus, which seems to indicate that the plants are capable of luxurient uptake of nutrient. Peltier and Welch (1969) observed nitrogen and phosphorus contents in P. pectinatus ranged from 20 to 34 mg/gm and 3.1 to 4.3 mg/gm respectively in a Tennessee reservoir. Gerloff and Krombholz (1966) estimated that growth would be limited in aquatic macrophytes when concentrations of N and P in plant tissue are below 13 mg/gm and 1.3 mg/gm respectively, suggesting that nitrogen must be applied in an N:P ratio of at least 10:1 if nitrogen is not to be growth-limiting.

Availability of nutrients is an important consideration in assessing a stream's potential to support aquatic plants. While in quiescent waters sufficient time is provided for originally unavailable forms of nutrient (usually long chain organically bound nutrients and nutrients associated with clay particles) to become available through bacterial activity, this is not the case in fast flowing waters. Walker et al. (1979) found that during the summer months large weed beds of P. pectinatus and C. glomerata in the Grand and Speed Rivers were capable of removing the filterable form of phosphorus, some of which is not termed reactive in the chemical analysis for soluble reactive phoshorus (SRP). At the same time the non-filterable forms were not apparently utilized in the weed bed. In each river reach the soluble reactive forms of phosphorus were almost totally depleted during the productive period of the day. This implies that these plants are capable of selective removal of nutrients and will remove the reactive forms first, then satisfy their remaining need with the filterable form of P (not

necessarily 'reactive' P). It was concluded in this study that filterable phosphorus or that fraction of the total which passes a 0.45μ filter is the best indication of available P in this type of ecosystem.

2.6 Hydraulic Conditions

Aside from nutrient, radiation and temperature conditions, the physical substrate and stream velocity must be suitable for the growth of the species C. glomerata and P. pectinatus in streams. These plant species have a preference for fast flowing, shallow water with a stony type of substrate.

Neil and Owen (1964) found that Cladophora in lakes grows best in nearshore environments where littoral currents are in the order of 30 feet per minute. Amberg and Cormack (1960) concluded that velocity requirements are actually related to nutrient requirements as these plants require a large steady flux of nutrients. These velocities also provide for a firm, stable, low silt substrate for the plants to attach to. Zimmerman (1961) found that Cladophora grew best at velocities of 80 cm/sec in sewage flow of reduced nutrient concentrations while at higher nutrient concentrations a velocity of 20 cm/sec. gave a similar growth rate. Bellis and McLarty (1967) noted that Cladophora grows best in water which can impart a waving motion to the filaments, thereby sweeping away plant by-products and constantly bringing nutrients into contact with the algal cells.

Whitford and Schumache (1965) found that when currents exceed 15 cm/sec a steeper diffusion gradient is produced around plants. They conclude that an "inherent current demand" is actually a need for rapid exchange of materials between plant and water. Their experiments with a freshwater macrophyte showed that phosphorus uptake was 10 times higher in a current of 18 cm/sec than in still water.

McIntire (1965) obtained similar results for communities of periphyton in laboratory streams. In this study higher biomass densities and higher productivity occurred in an artificial stream with a current velocity of 38 cm/sec compared to one with a current velocity of 9 cm/sec.

As well as preferring a fast flowing environment, these species of plants, when in dense beds can disturb the flow. Cladophora and P. pectinatus are often found in riffle areas of streams which act as control points for the upstream section, regulating depth and stream velocity.

Kouwen et al. (1969) found that artificial grass in a laboratory channel had the effect of increasing depth, increasing channel roughness and retarding flow. Gourlay (1970) followed this work by examining flow regimes in a stiff grass under various slopes. He found that velocity within the grass near the stream bed was very low and constant with depth. Flow was essentially forced to travel over the top of the grass bed. Walker et al. (1979) found that C. glomerata and P. pectinatus in the Speed River were able to significantly increase the roughness coefficient of the stream (Manning's n) when the densities were above 200 gm/m^2 during low flows. When biomass attained a density of 800-900 gm/m^2 the Manning's n increased by 33%. This perturbation was shown to have a significant effect on upstream depth and reaeration coefficient.

3. Methods

3.1 Introduction

This section contains brief descriptions of the field and laboratory data collection procedures as well as the techniques used to analyse these data. A more complete version of the field and laboratory methods is included in the Grand River Basin Water Management Study Technical Report #15 entitled "Plant Community Assessment Techniques - Data Collection and Field Procedures" (Walker and Willson, 1981).

3.2 Field Studies

3.2.1 General Description

An intensive field data collection program was conducted in 1978 on two reaches in the Grand River basin. One of the reaches is on the Grand River near Conestogo (Figure 14.) This reach was selected because of its relatively low nutrient concentrations, ease of access and suitability for attached aquatic plants. Data from this reach were used to calibrate the model. The second reach studied and later used in model verification is located on the Speed River near Glen Christie (Figure 14). It exhibited higher nutrient concentrations (compared to those of the Grand River reach), thus creating ideal conditions for plant growth and has been observed to support a high biomass in past years . Physical characteristics of the two reaches are listed in Table 3. Both are located several miles downstream of significant point source inflows. There are a number of point source discharges of treated effluent upstream of the Grand River reach; however, each of these plants is fairly small. The reach on the Speed River is located below the City of Guelph. The main point source of treated effluent is from the Guelph water pollution control plant, discharged into the Speed River approximately four km upstream of the study reach. Both reaches receive nutrients from agricultural areas as well as from rural runoff. Oxygen and temperature were continuously monitored at each end of these reaches. Regular flow measurements were made and biomass densities were estimated on several occasions. Water quality, the optical properties of water and solar radiation were measured routinely. Those procedures are outlined below.

3.2.2 Hydraulics

Cross-sectional depths were measured at each major change in depth or width in each reach. Total length and elevation change were also measured, allowing for an estimate of total surface area. Staff gauges were placed in the stream at the upstream and downstream stations and water elevations were recorded at least twice a day. Time-of-travel or residence time in the reach was estimated at a variety of flow rates using a dye tracer (Rhodamine WT) measured

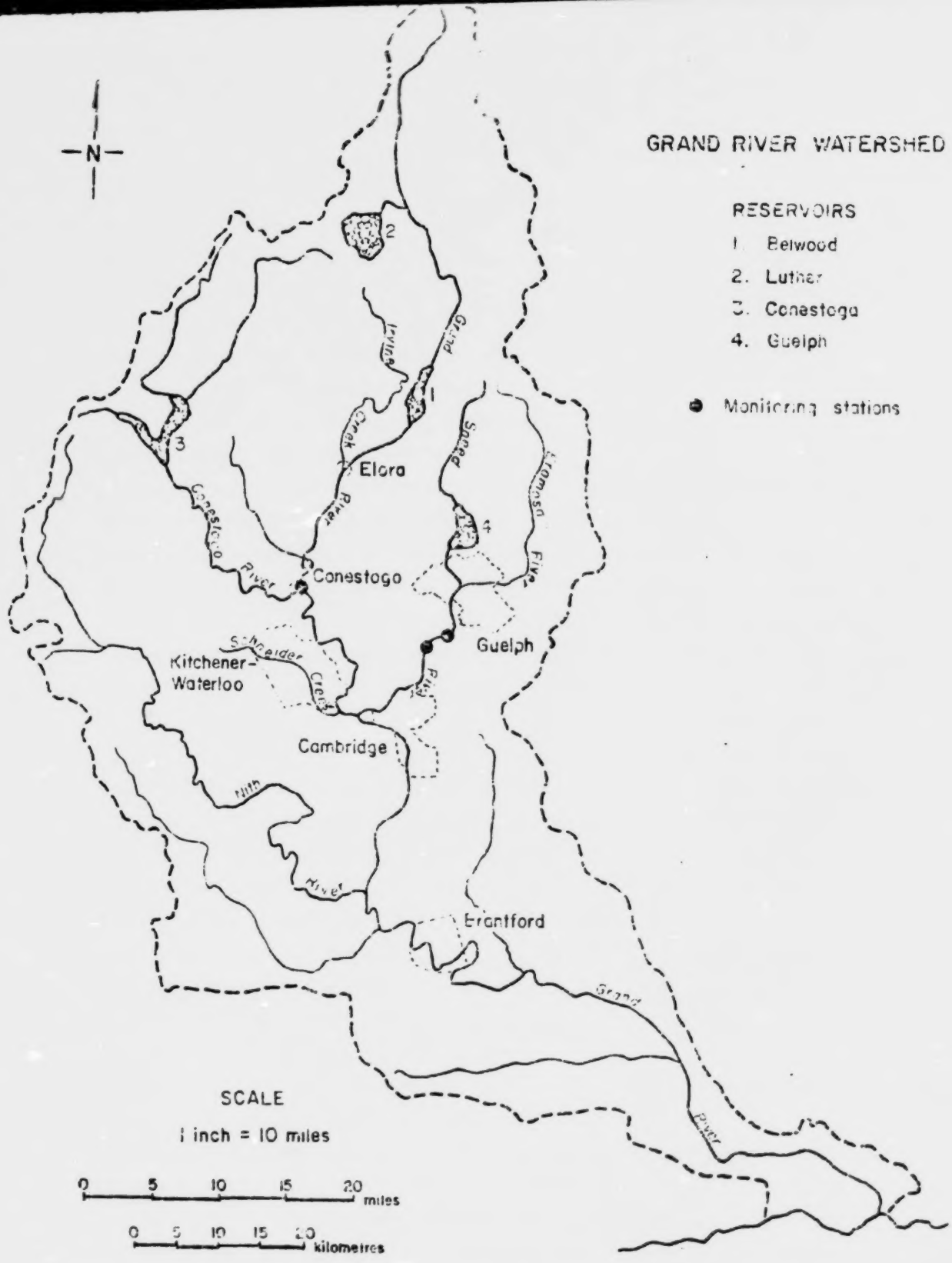


Figure 14: Study reach locations

Table 3

Study Reach Physical Characteristics

Reach	Length (m)	Average Width at Low Flow (m)	Average Depth at Low Flow (m)	Bed Surface Area m^2	Substrate Type
Grand R. Km 190-193	3120	56.0	0.30	175,000	Stony
Speed R. Km 166-167	1780	38.5	0.22	60,000	Bedrock-Stony

with a fluorometer (Turner Design Model 10-05.). Flow rates were measured several times throughout the study period with a Marsh-McBirney electromagnetic water current meter.

Measurements of morphometry and flow rates allowed for the development of a relationship between staff gauge height and flow rate, flow rate and time-of-travel, and flow rate and mean depth. These relationships are necessary in the productivity analysis which is discussed later.

3.2.3 Dissolved Oxygen - Temperature

Dissolved oxygen meters (EIL) with Rustrak recorders were located at the upstream and downstream boundaries of the study reaches. These meters provided continuous traces of oxygen (in percent saturation units) and water temperature (in ^{o}C). Regular calibration was provided using the Azide Modification of the Winkler Analysis for dissolved oxygen (WPCF, 1975). The temperature and DO probes were located on the downstream side of a coarse screen in mid-stream. The screens reduced probe fouling and damage by floating material. Interruptions of data traces were reduced by frequent equipment calibration and servicing. This equipment operated in this manner from early April 1978 to mid-September 1978 at four stations (ie., two in each reach). This information provided the needed data to conduct the Odum's (1956) analysis for stream productivity on these reaches.

3.2.4 Biomass Density and Washout

The biomass density in each reach was estimated using two methods at regular time intervals. In one of the methods, plants were cropped by hand from 1 square foot quadrats at marked locations along each reach. In all, about 50-75 quadrats were cropped in each reach at about three week time intervals. The cropped material was placed in bags, dried in an oven in the laboratory at $100^{o}C$ for two hours and weighed. Results were then obtained as dry weight per square foot and averaged for the entire reach. Several samples were analysed for P and N in the tissue.

The second biomass estimation method involved aerial photography. On four evenly spaced occasions during the summer of 1978 low altitude photographs were obtained; the flights were coordinated with biomass croppings. It was possible to extrapolate quadrat densities at known locations according to the apparent extent of plant infestation from the photographs. This method, in coordination with field cropping, allowed for extrapolation to a large area, including hard to reach locations.

Washout of plant material was observed in a cursory manner using a screen trap placed in the stream at each station. Trapped plant material was removed from the screen, dried and weighed when a significant amount had accumulated. Rates of accumulation of plant material caught in this way could be compared between the upstream and downstream stations. Also, the effects of significant washout events could be observed despite the time of day at which the event occurred.

3.2.5 Water Quality

Water samples were collected once each day at each station. The downstream stations were sampled approximately one time of travel after the upstream sample had been collected. It was hoped that this procedure would result in the sampling of the same 'plug' of water and therefore an estimate could be obtained of the net effect on the "plug" of chemical dynamics in the reach each day. These data could then be compared to results of the productivity analysis in order to establish appropriate causal relationships.

Water samples were analysed for total phosphorus (TP), filterable phosphorus (FP) and filtered reactive phosphorus (FRP), nitrate (NO_3) and ammonia (NH_3). Samples requiring filtration were filtered in the field and all samples were kept on ice until analysed. Turbidity was measured *in situ* at each station daily.

3.2.6 Radiation and Light Extinction

Solar radiation was monitored at Cambridge during the growing season in 1978. As well, underwater light extinction was estimated each

day at each station according to the method used by Wong et al. (1976). This information led to daily estimates of the extinction coefficient, Ke, which can be related in turn to water turbidity values.

The quantum sensor used to measure underwater light records photosynthetically available radiation, while the pyranometer used to measure solar radiation records a broader portion of the total electromagnetic wave band. Measurements at ground level were made using the quantum sensor on several occasions under various atmospheric conditions. These values were compared to instantaneous solar radiation values measured at the same time. This information was used to establish a relationship between atmospheric conditions and the percentage of radiation which is photosynthetically available.

3.2.7 In Situ Respiration Measurements

Substrate pans were placed in the streams in the spring and allowed to develop periphyton communities similar to that of the entire stream benthic area. These pans were constructed in such a manner that respirometers could be fitted and sealed over them. Several times each week respiration rates were measured over the substrate pans. Respirometers were transparent (ie. permitted light penetration) and allowed for continued photosynthesis of the periphyton. Opaque respirometers were also used to estimate periphyton respiration rates.

Ordinary floor tiles were fixed to a plank, anchored in each stream facing upward, as a surface of attachment for periphyton cells. At regular time intervals plates were removed, used for respiration measurements in the laboratory, scraped and replaced in the stream.

3.3 Laboratory Methods

Respiration was measured on small quantities of Cladophora, P. pectinatus and periphyton throughout the summer. Batch reactors in which small samples of plant material could be placed, were filled with water which was continuously circulated. The reactors were maintained in temperature-controlled baths and the dissolved oxygen and temperature within were measured and recorded. Reactors were kept in the dark to prevent photosynthesis. After several hours, at which time oxygen would be significantly reduced inside the reactors, the plant material was withdrawn, dried and weighed. This procedure allowed for the calculation of unit respiration rates for the three plant groups at various temperatures. Clean fresh plant material was used throughout these measurements.

3.4 Data Analysis

In this section the methodology employed in estimating productivity is discussed. Computer programs developed for this purpose are fully explained in the GRBWMS Report #15 entitled "Plant Community Assessment Techniques - Data Collection and Field Procedures".

Productivity analysis estimated from stream oxygen cycles was first proposed by Odum (1956). This technique separates the causes of stream oxygen dynamics into three independant processes; plant respiration, plant productivity and physical reaeration. Nightime data are used to calculate the reaeration coefficient and the respiration rate assuming both are constant. Productivity is then calculated on an hourly basis for the daylight period. The method is based on the assumption that homogeneity of physical and biological characteristics exists in the reach.

Two methods are available, both suggested by Odum. In the first, termed the "two-station method", two D.O. meters are used and the analysis is performed on the reach between the meters. The analysis proceeds with the time of travel changes in stream oxygen concentration. This method involves a more detailed knowledge of

streamflow and requires duplicate monitoring stations. The second method is the so called "single station method" in which one station only is required. This method involves calculating the hourly changes in dissolved oxygen and makes the assumption that upstream dissolved oxygen concentrations are uniform. (Note that this assumption can lead to significant errors in interpretation.) Both the "two station" and "single station" methods were employed in this study.

The Odum analysis yields hourly, daily and instantaneous maximum community productivity in terms of oxygen transfer, daily reaeration and hourly respiration rates. When combined with environmental, meteorological and standing crop conditions, much can be learned about plant metabolic activity. Results of this analysis will be discussed in the next chapter, since they apply to model development.

4. Model Development and Discussion

4.1 Light Submodel

4.1.1 Extinction in Water

Correlations were established between extinction coefficients and turbidity for each study reach. Resultant regressions for the Grand and Speed River reaches appear in Figures 15 and 16 along with regression equations and "r's", the correlation coefficients. For simplicity, and to approach a degree of universality with the model, an average relationship was taken as the numerical average of the Grand and Speed regressions. This regression appears as,

$$Ke = 0.21 \cdot TURB + 0.34 \qquad (11)$$

The individual regressions were very similar.

Relatively low regression coefficients result in part from measurement error (measured Ke values have a large confidence limit) and partly from a relatively low range in actual conditions, accounting for a tendency for the data to cluster, making linear

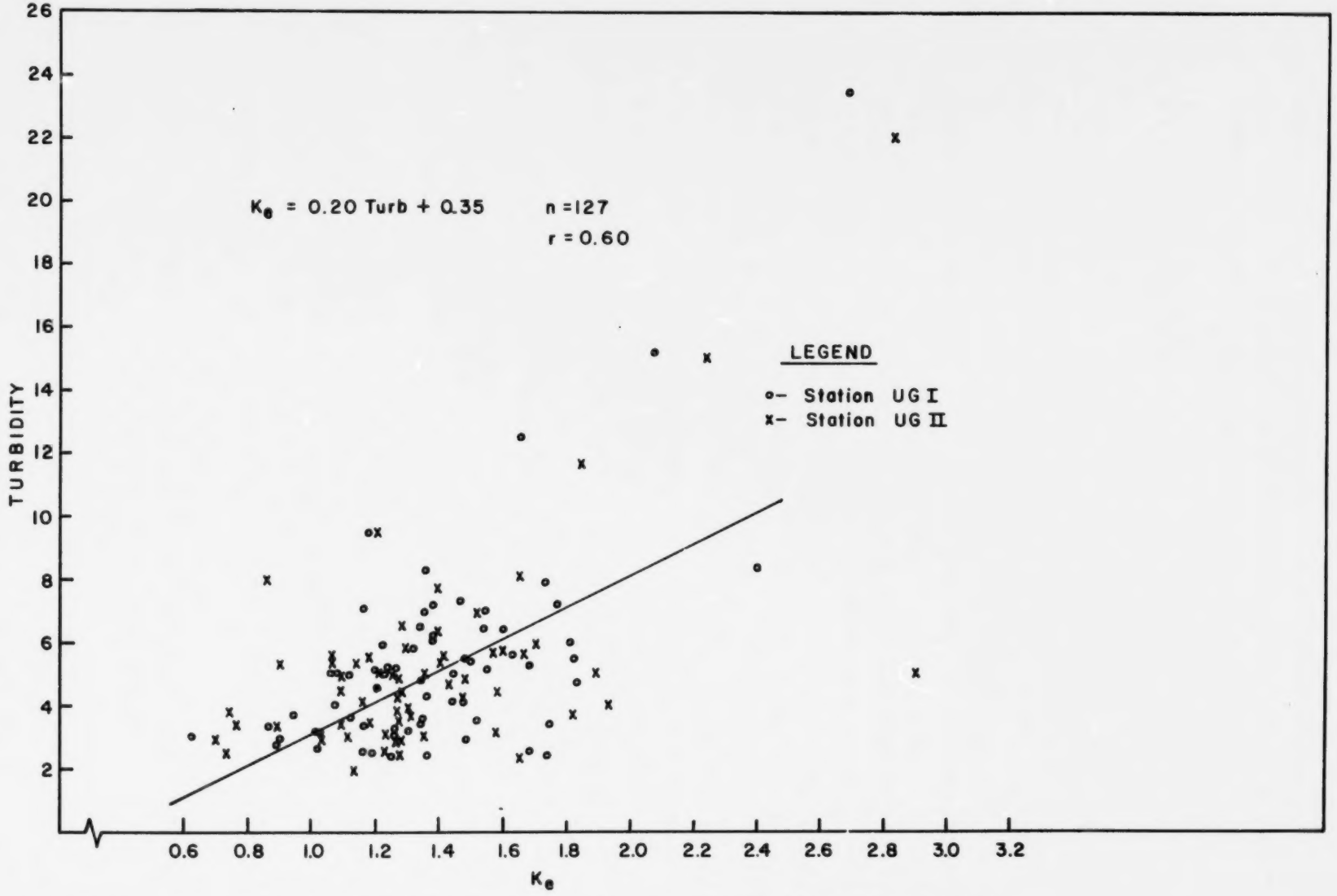


FIGURE 15 TURBIDITY VERSUS THE LIGHT EXTINCTION COEFFICIENT ,K_e, IN THE GRAND RIVER.

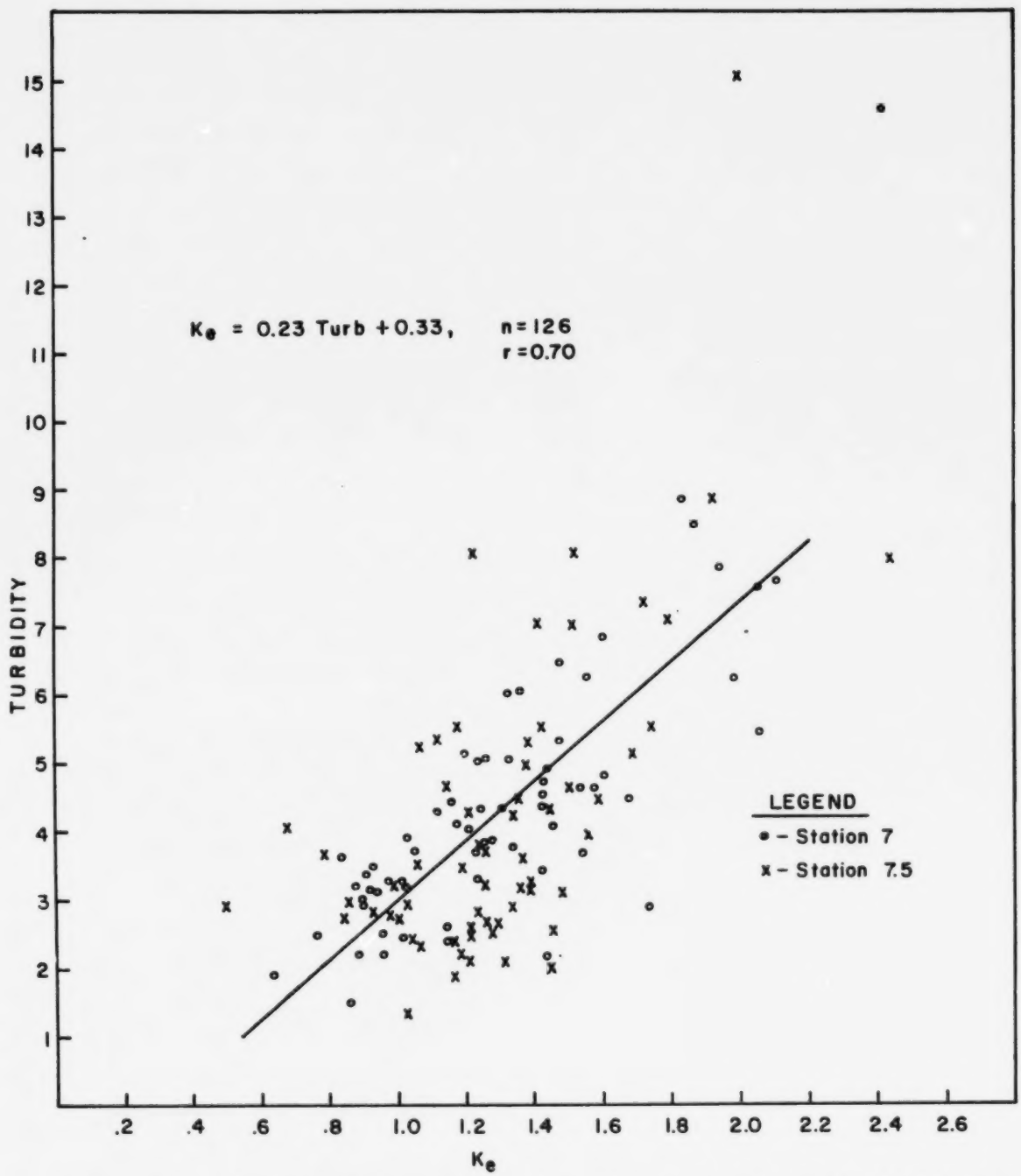


FIGURE 16 TURBIDITY VERSUS THE LIGHT EXTINCTION COEFFICIENT, K_e, IN THE SPEED RIVER.

regression inconclusive. The regression technique is useful, however, in that Ke can be estimated from a simple turbidity measurement eliminating the need for sophisticated quantum sensing equipment; however, confidence limits are necessarily broad.

4.1.2 Photosynthetically Available Radiation (PAR)

Only a portion of the total solar electromagnetic radiation is available to plants as an energy source. Plant pigments are specific receptors of narrow bands of wavelength between 400 and 750 nm (nannometer). Instantaneous ground level measurements made with a pyranometer (total solar radiation) were compared to measurements from a quantum sensor (PAR). Atmospheric interference was quantified in relative terms by comparing total radiation values with theoretical calculations of solar radiation at maximum atmospheric altitude from Won (1978), to be discussed in the next section. No significant relationship was found between atmospheric conditions as percent sunniness and the percentage of total radiation which is photosynthetically available. The percentage of total radiation which is photosynthetically available was found to vary from 46 to 62% with a mean of 53%. This value was used in the model to estimate available radiation from total radiation.

4.1.3 Theoretical Radiation and Back Reflection

A theoretical solar radiation model was adopted from the model of Won (1978) to predict theoretical solar radiation at the top of the earth's atmosphere. This model uses as variables the julian day, time of day, and latitude. The model also calculates the angle of incidence of the sun, which is necessary in estimating back reflection from the water surface. The angle of incidence and theoretical radiation are calculated as,

$$\cos \quad = \cos \quad \cos \quad \cos \quad t + \sin \quad \sin \qquad (12)$$

where is the zenith angle, is the declination, t is the solar hour angle and Ø is the latitude. In this equation

$$= 0.3964 + 3.631 \sin \quad - 22.97 \cos \quad + 0.03838 \sin 2 \quad - 0.3885 \cos 2 \quad + 0.07659 \sin 3 \quad - 0.1587 \cos 3 \quad - 0.01021 \cos 4 \qquad (13)$$

where $\alpha = \frac{JD}{365} \times 2$ (14)

and JD is the julian day. The term ωt is further broken into ω, the angular velocity of earth (0.262 radians/hr.) and

$$t = 12 - TST \quad (15)$$

where TST is solar time. These calculations then lead to the formulation of the angle of incidence (AI),

$$AI = 1.571 - \frac{\sqrt{1-(\cos\theta)^2}}{\cos\theta} \quad (16)$$

Before calculating theoretical radiation the relative distance between the earth and sun r/r_o must be estimated as

$$r/r_o = 1.0-0.0009464 \sin\alpha - 0.0167 \cos\alpha -0.000149 \cos 2\alpha$$
$$-0.0000292 \sin 3\alpha \quad -0.000344 \cos 4\alpha \quad (17)$$

This allows for the calculation of the theoretical radiation (ITHEOR) as

$$ITHEOR = 115.83 \times \left(\frac{r}{r_o}\right)^2 \times \cos\theta \qquad \text{(in langleys/hr)} \quad (18)$$

A term called percent sunniness (SUN) was devised for this study and is equal to the percentage of instantaneous theoretical radiation observed at ground level. This term, therefore, is a lumped estimate of total atmospheric scatter and interference. As stated elsewhere, Figure 4 (presented in chapter 2) illustrates the effect of atmospheric interference on surface reflection or back reflection (BR) of light throughout the range of angles of incidence. To simulate this effect, the three curves of Figure 4 (A, B and C) were represented by the equations,

(A, clear) $BR = 104.4\ e^{(-6.29.AI)}$ (19)

(B, moderate cloud) $BR = 17.5\ e^{(-0.86.AI)}$ (20)

(C, overcast) $BR = 10.6\ e^{(-0.65.AI)}$ (21)

The follwing criteria were chosen for selection of a BR equation: if instantaneous

	SUN	>	55 : equation 19 is used,
	if SUN	>	35 : equation 20 is used
or	if SUN	<	35 : equation 21 is used.

These models are more representative of solar radiation entering the water column under various conditions of solar angle and atmospheric condition.

4.1.4 Radiation Model

A model similar to the Beer-Lambert equation was chosen to represent the response of photosynthetic activity to PARD (photosynthetically available radiation at plant depth). The trends of growth versus radiation reported in the literature are well represented by this formulation, which in this model appears as

$$RADFAC = \frac{PARD}{K_I + PARD} \qquad (22)$$

where RADFAC is a radiation factor which is always less than 1.0 and K_I is an empirical constant equal to the solar radiation when RADFAC = 0.5. The value of K_I was determined by calibration. Figure 17 illustrates the shape of this model with various values of K_I when units of langleys/min are used. PARD seldom exceeds 0.5 langleys/min and in this range the model is very sensitive to values of K_I.

4.1.5 Self Shading

A model was developed to reflect the increasing inhibition to growth as biomass densities increase. Westlake (1966) presented this phenomenon in the graphical form illustrated in Figure 2 (see Chapter 2). A term was developed called SHADE which is multiplied by the term RADFAC discussed in the previous subsection. SHADE has

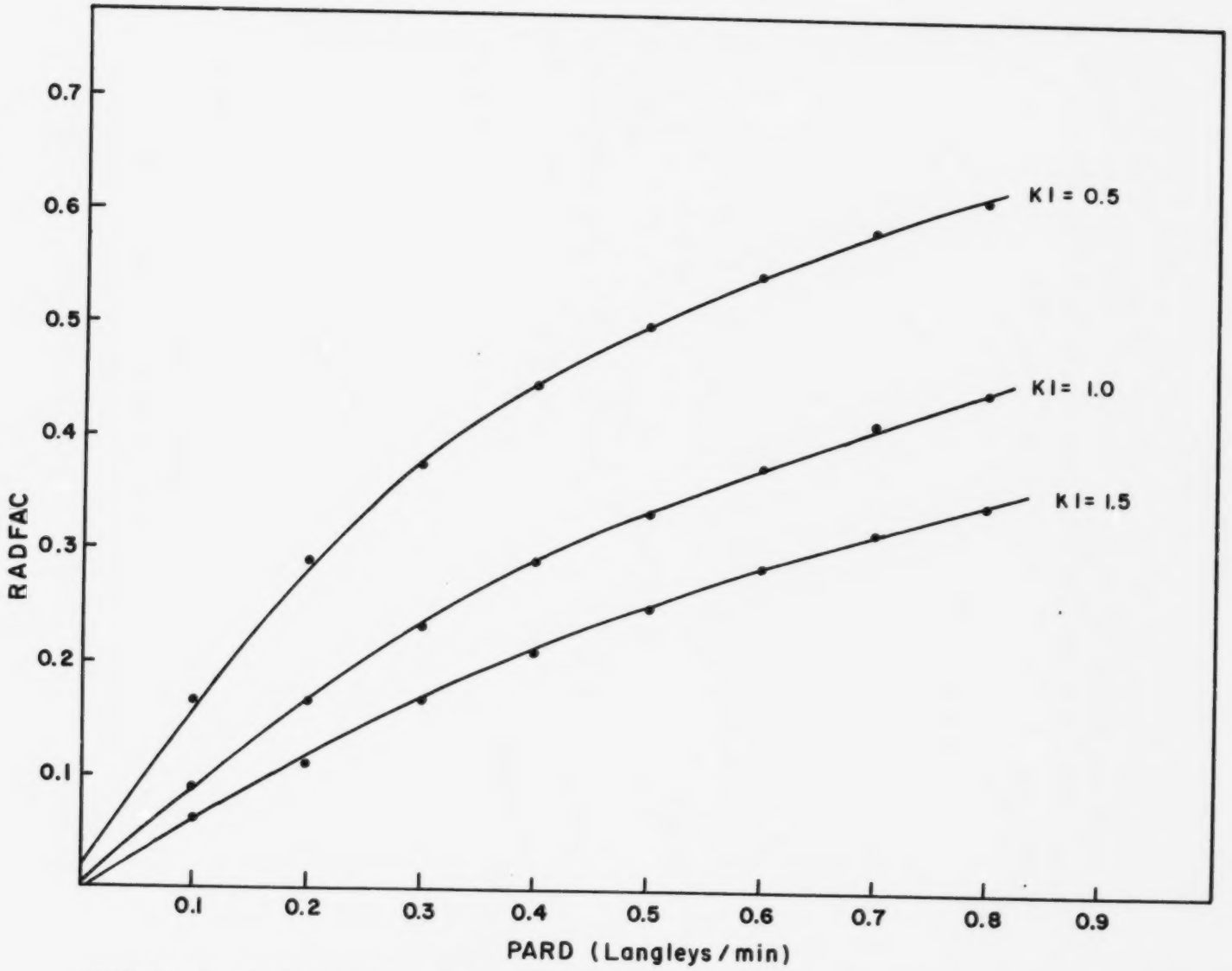


FIGURE 17 RADIATION MODEL SHAPE AS A FUNCTION OF PARD. (PHOTOSYNTHETICALLY AVAILABLE RADIATION AT PLANT DEPTH)

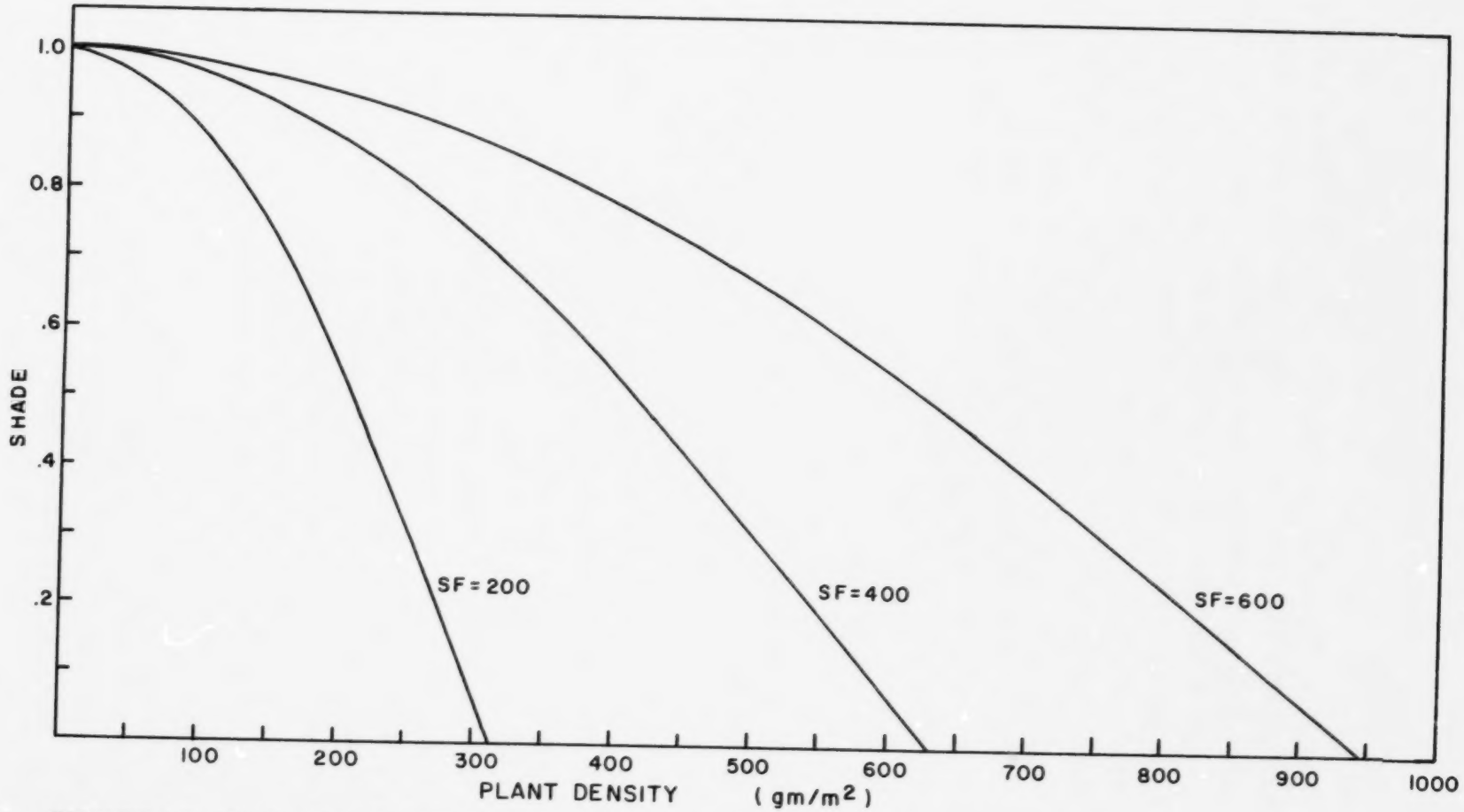


FIGURE 18 THE SHADE MODEL AS A FUNCTION OF PLANT DENSITIES.

values which do not exceed 1.0 and decrease as biomass density increases in the equation

$$SHADE = \cos\left(\frac{PD}{SFx}\right) \quad (23)$$

where PD is the density of the total biomass and SFx is a factor representing the upper limit of density for any species and is specific to each species. These values vary from 90-1200 and were refined in the calibration process. Since Cladophora and P. pectinatus tend to form wavering floating mats and cannot be totally self shaded, a lower limit was placed on SHADE of 0.5. In the case of periphyton, the lower limit is 0.1, since periphyton is largely limited to growth on the stream bottom and is highly subject to shading by Cladophora and P. pectinatus. Figure 18 illustrates the shape of this model and predicted values of the SHADE factor at various SF values.

4.2 Temperature Submodel

4.2.1 Laboratory Respiration Studies

Laboratory respiration studies on fresh plant samples were conducted throughout the summer of 1978, in order to gain insight into plant respiration rates and temperature related trends. Figures 19, 20 and 21 show individually determined rates of oxygen uptake by known weights of pure plant material. Figure 19 illustrates the results obtained for periphyton communities. In this case the rates are most likely underestimated since considerable error occurs when estimating the mass of healthy periphyton in each reactor experiment. Visual observation indicated that non-viable cell material and inorganic material was often included in the sample, increasing apparent weight and reducing the apparent unit respiration rate. The trend of the data is clear, however, indicating a Q_{10} of 2.96, a figure consistent with those reported in the literature.

Figure 20, for P. pectinatus, indicates that one gram of dry plant material, when healthy, respires at a rate of about 0.0036 gm O_2 per hour. Using the stoichiometry of Aiba and Ohtake (1977), in

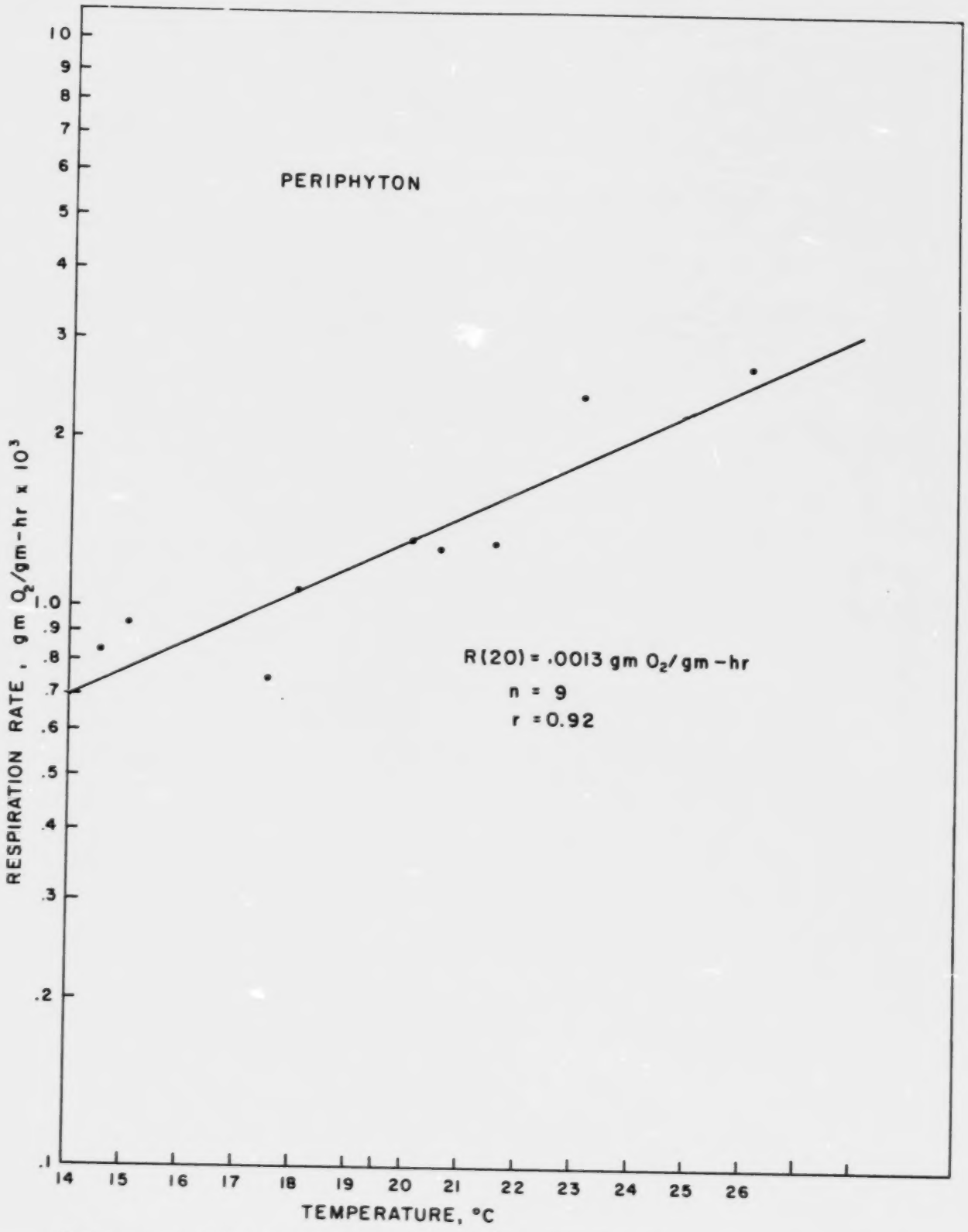


FIGURE 19 UNIT RESPIRATION RATE OF PERIPHYTON AS A FUNCTION OF TEMPERATURE.

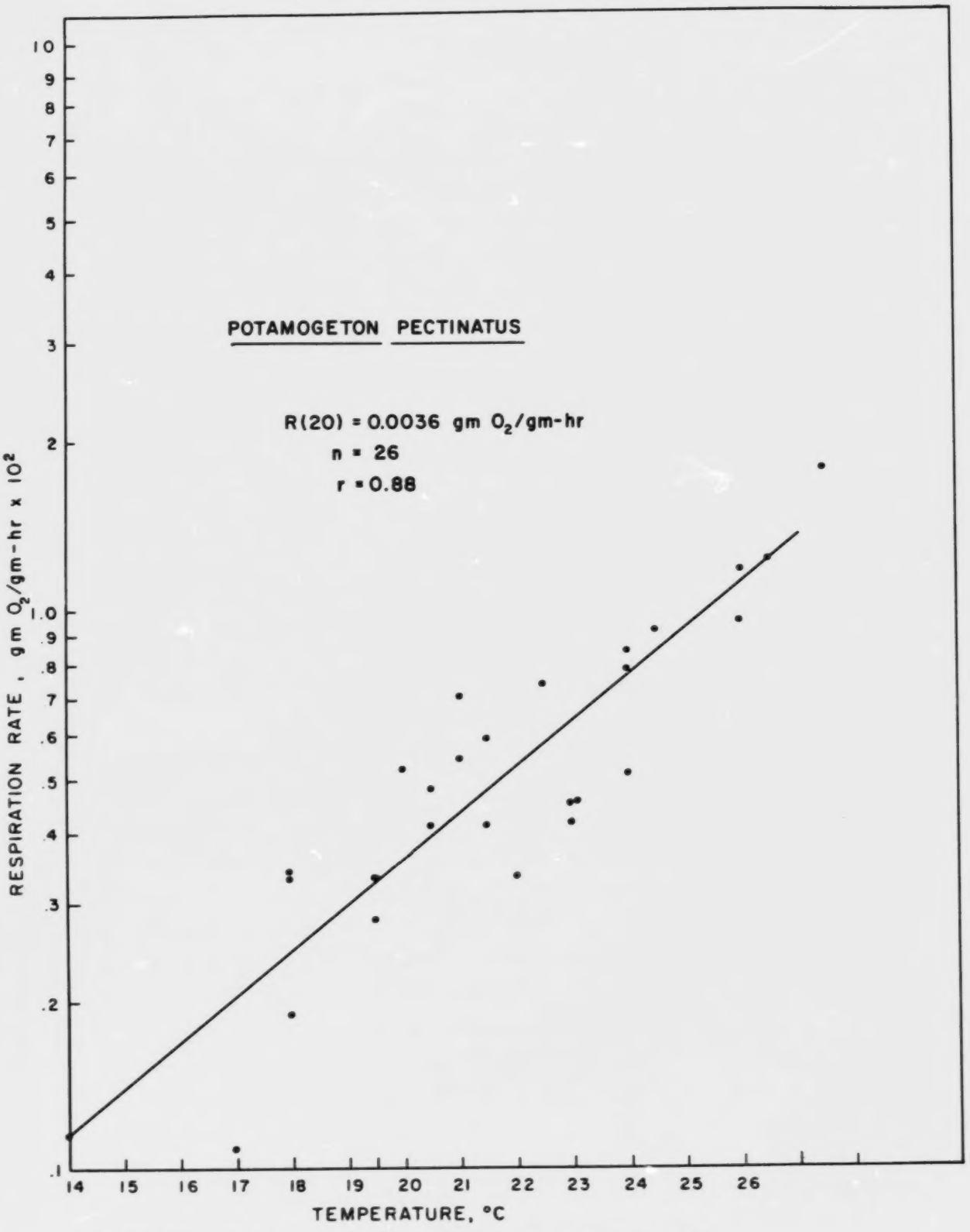


FIGURE 20 UNIT RESPIRATION RATE OF P. PECTINATUS AS A FUNCTION OF TEMPERATURE.

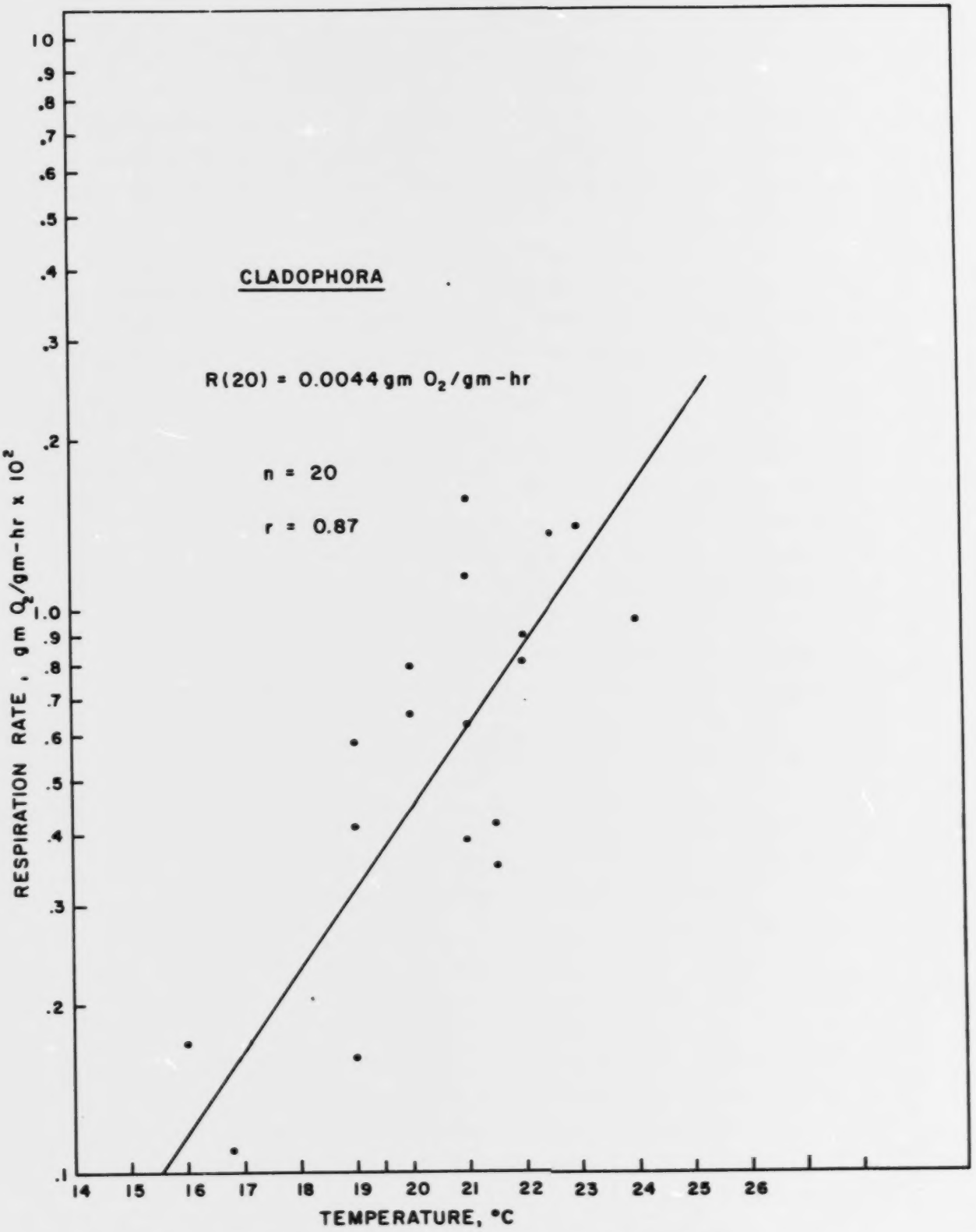


FIGURE 21 UNIT RESPIRATION RATE OF CLADOPHORA AS A FUNCTION OF TEMPERATURE.

which 1.55 grams of oxygen are consumed in the respiration of 1 gram of biomass, the unit respiration rate of P. pectinatus at 10°C would be 0.0023 gm of biomass per gm - hr. A Q_{10} of 6.5 is indicated by this regression. This is highly unlikely and is probably in part due to the relatively narrow range of temperatures applied (≈ 10°C). Reactor leaks and instrument calibration errors must also be considered in interpreting the results of the laboratory tests.

Figure 21 illustrates the regression achieved for the Cladophora unit respiration with R(20) being estimated at 0.0044 gm O_2/mg-hr or 0.0028 gm of biomass/gm-hr. As was the case with P. pectinatus Q_{10} values are surprisingly high.

This information assists in estimating species' unit respiration rates at typical temperatures. Final values were arrived at by model calibration procedures, and were very similar in magnitude. Temperature effects were overestimated in these experiments, probably due to experimental error and scatter of data.

The model form chosen to represent temperature trends, a power function, is common in biological systems and appears here as

$$R(T) = R(20)\ \theta^{(T-20)} \qquad (24)$$

where R(T) is the unit respiration rate at temperature T. The term θ is an empirical constant with a value between 1.0 and 1.2 in typical systems. The final value of θ was determined in model calibration.

4.2.2 Productivity

Separate models were used to describe the effects of temperature on photosynthetic biomass production. The model described in Section 2.3 was found to be suitable in reflecting the trends observed in the stream productivity analysis for Cladophora and P. pectinatus. These models appear as

Cladophora: $$Kcg = e^{(0.35(T-20))} \cdot \left(\frac{25 - T}{5}\right)^{1.7} \qquad (25)$$

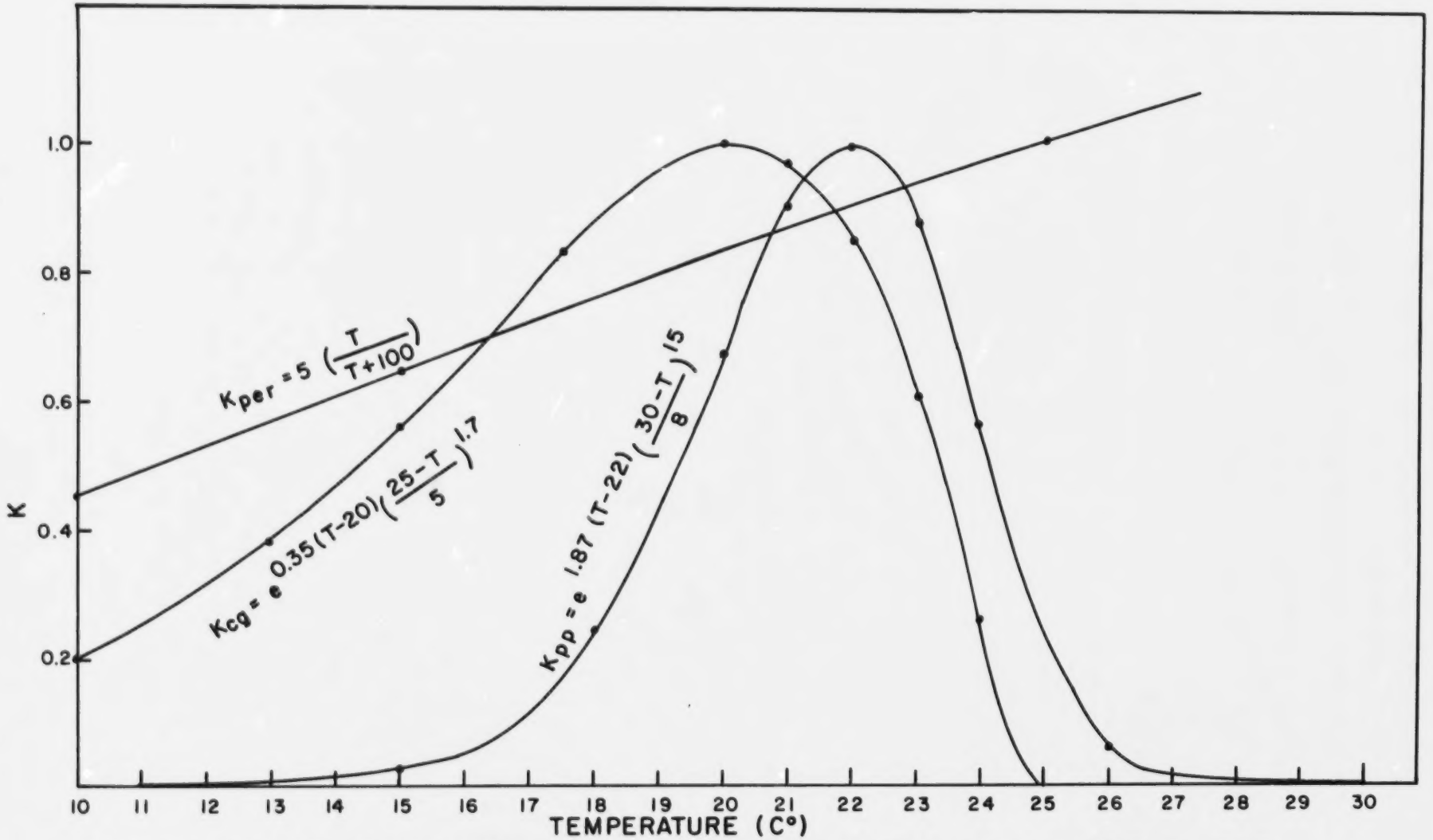


FIGURE 22 PRODUCTIVITY VERSUS TEMPERATURE SUB-MODELS FOR THREE PLANT TYPES.

$$\underline{P.\ pectinatus}: \quad Kpp = e^{(1.87(T-22))} \cdot \left(\frac{30 - T}{8}\right)^{15} \qquad (26)$$

$$\text{periphyton sp.}: \quad K_{per} = 5.0 \cdot \left(\frac{T}{T + 100}\right) \qquad (27)$$

Figure 22 illustrates the shape of the temperature sub-models determined in model calibration. The model used for periphyton is also included. Note that predominant temperatures in the range of 15°C to 20°C will heavily favour Cladophora dominance while temperatures between 22°C and 26°C will favour P. pectinatus dominance. Periphyton appears to grow well at all temperatures; however, shading is much more restrictive for this plant group. The growth term of species is simply multiplied by the specific unit growth rate of that species to account for the effects of temperature.

4.2.3 Washout and Death

The occurrence of relatively high or low stream temperatures can place a great deal of stress on plants resulting in rapid death and subsequent scouring. This has been observed in the Grand River. Excessive temperature (>25°C) causes the Cladophora to turn brown, thereby losing its productive capability, and to turn brittle to the touch. Gradually or suddenly, in the event of high flows, the biomass is washed from the stream bottom. Plant material can often be seen floating downstream, or caught on low hanging tree branches, following rainfall events, high temperature spells, etc.

A washout event was observed in 1978 on the Grand River study reach. Temperatures exceeded 26°C in the stream predominantly populated by Cladophora at that time. Shortly after, streamflow increased from 5 m^3/s to about 15 m^3/sec as the gates at the upstream reservoir at Belwood were opened. A majority of the plants were washed away in less than 48 hours.

Screen sample collection rates did not relate to stream parameters on a day to day basis; however large quantities of plant material gathered on screens during high-flow events such as the one described above. It is very difficult, therefore, to formulate a descriptive model of the washout process. A degree of success was,

however, achieved with the following washout expressions,

Cladophora: $WASHOUT = ((T-25)^5 + 0.06) \times CLAD$, $T > 25$

$= 0.001 \times CLAD$, $T < 25$ (28)

P. pectinatus: $WASHOUT = (0.03 - (0.002 \cdot T)) \times POT$, $T < 15^{o}$

$= 0.001 \times POT$, $T > 15$ (29)

periphyton $WASHOUT = 0.001 \times PERI$ for all temperatures (30)

In the above relationships, CLAD, POT and PERI are the areal densities of the three plant types. Note that there is always a small degree of washout predicted and observed. However, when certain temperature conditions are met, washout will occur at an increased rate. These models are highly speculative and their use is only justified by the degree of success achieved in the model testing process in which they were included. Further work is needed in examining such extreme events.

4.3 Nutrient Submodel

A plant's nutrient requirements are determined by its instantaneous growth rate which is a function of stream temperature and available radiation. Whether or not this demand will be supplied is dependant on the nutrient flow rate or flux in the stream and the mass of plants exerting this demand. In sparsely populated stream sections plants can be adequately supplied by a relatively low nutrient flux while dense weed beds will tend to limit growth downstream by depleting nutrient supplies. When supply exceeds demand for phosphorus, plants can store phosphorus in the cell tissue. This storage material can be drawn upon to meet some of the plant's needs when demand exceeds phosphorus supplied by the stream. However, this does not occur with nitrogen (Wong et al., 1976). The effect of this phenomenon is that plants existing in moderate to low nutrient waters may have their nutrient needs satisfied during the early and late portion of the photoperiod and may be able to store

excess phosphorus. However, during the peak growth hours (1200 - 1600 hrs) these plants may experience some nutrient limitation, necessitating utilization of stored stocks of phosphorus. This effect may also be apparent on a seasonal time scale as nutrient limitations only occur in a reach when densities exceed the value which can be optimally supported.

Nutrient supply in the model is calculated for each time step, on a reach-by-reach basis by the equation:

N or P Supply = Reach volume x (N or P) Concentration (31)

Time steps and reach sizes must be selected to result in a minimum iterative error. Nutrient requirements are calculated by the general equation:

N or P demand = Growth rate x (N or P) Assimilation Ratio x
Biomass density x Reach area x Efficiency Factor (32)

In effect, this method considers the instantaneous reach demand and subjects that value to an efficiency factor which is greater than 1.0 (When the efficiency factor = 1.0, the plants utilize 100% of the instream P.) The Assimilation Ratio is a stoichiometric ratio of N or P uptake related to biomass synthesized.

Several nutrient supply possibilities exist; they are treated separately by the model. First, if supply exceeds demand plant growth can proceed uninhibited. In this case the plant may be able to store a portion of the excess phosphorous in tissue. If demand exceeds supply the plant must draw upon stored supplies of phosphorus to meet the demand. If no stored stock exists then plant growth is limited to a fraction of that which would have occurred under optimum nutrient supply conditions. Growth is factored in this case by multiplying the optimum growth rate by the ratio of nutrient supplied to nutrient demand. The quantities of nutrient taken from or placed in storage were assigned in calibration to satisfy observed plant nutrient trends and observations in the study reaches.

In the model, only P or N can limit the growth at any one time, since it is unlikely that simultaneous nutrient shortages could occur. This would occur only if growth were a second-order reaction with respect to P and N.

Figure 23 illustrates the trends observed in the Grand River in 1978 between phosphorus flux and total phosphorus in plant tissue (PINP). In this figure, only those days when solar radiation was moderate to good are included. The out-flux from the reach and estimated net uptake are also plotted. These values are calculated for peak production hours only. Note that PINP decreases during July at which time P flux was also lower.

4.4 Biomass Estimates and Seasonal Trends

Productivity analysis using the Odum's method (Walker and Willson, 1981) resulted in daily average respiration rates in the Grand River study reach. These estimates yield a total community respiration rate. The values were standardized to 20^{o}C using the temperature correction model (Section 4.2), Equation 24, where θ is equal to 1.1, which represents an average value obtained in model calibration. The seasonal estimates of R(20) are shown in Figure 24; considerable differences in R(20) values can be found on consecutive days. These differences are not likely due to real changes in the biomass, but most likely due to errors in analysis or measurement. However, the trends observed follow distinct patterns. In the early summer Cladophora glomerata dominates the biological community and observed respiration rates reach highest levels. In late June, stream temperatures are high and the Cladophora community is almost completely washed away, to be replaced by a Potamogeton pectinatus community. Respiration rates during the period July-August are lower and more stable until there is a decrease to very low respiration in late August. As stream temperatures decrease in September, respiration rates are seen to increase as Cladophora again reappears and begins to dominate the community.

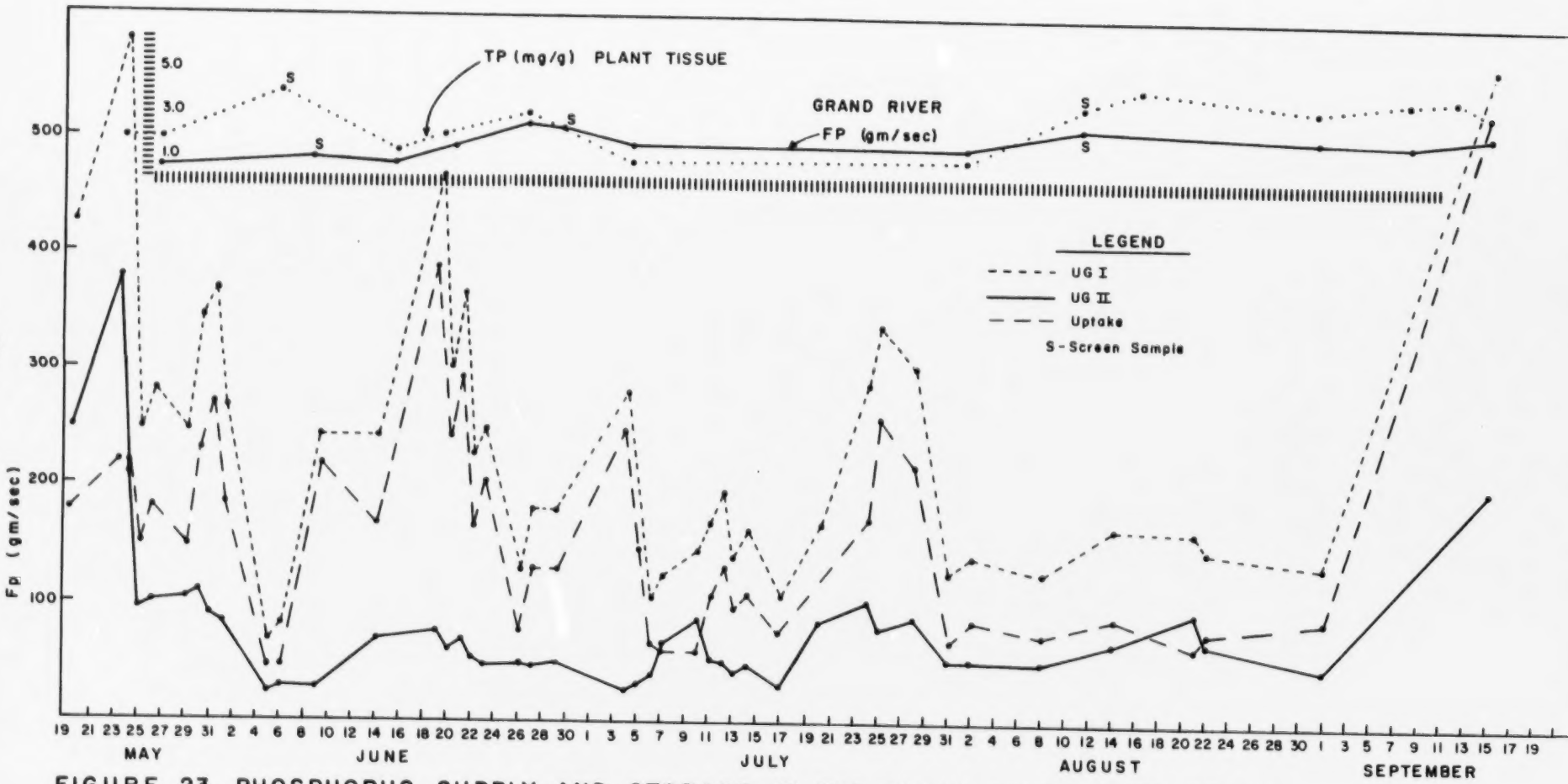


FIGURE 23 PHOSPHORUS SUPPLY AND STORAGE IN THE GRAND RIVER STUDY REACH.

The respiration rate at 20°C is a good indicator of the total biomass present. If a unit respiration rate of 0.0045 gm O_2/gm biomass-hr. is used to estimate biomass density, the curve shown in Figure 25 is obtained. A confidence interval is used here to indicate the degree of certainty associated with this method. As well, biomass estimates made on seven occassions from cropping data and in some cases aerial photography are included here. These values agree well with those estimated from respiration rates. Cropping will usually lead to an underestimate of the total biomass density, since periphyton biomass will not be included. On the other hand, community respiration estimates include bacterial respiration as well. If this component is not subtracted, the resultant estimates will be an overestimate for plants.

In 1978, the Speed River study reach responded somewhat differently in comparison to the Grand River reach. Figure 26 shows the estimated seasonal biomass. (In this case the respiration method was not used since the Speed River displays very high bacterial respiration rates at this location. This interference makes biomass estimation from respiration more difficult.) Biomass estimates from cropping and aerial surveillance are included. The confidence interval arrived at is based on the observations of general conditions derived from the Grand River biomass data.

The Speed River had a predominantly periphyton and moss type of community in May. The Cladophora community dominated and grew very dense by mid July. Possibly, higher shading allowed this community to survive relatively high stream temperatures in late June. However very high stream temperatures (> 26°C) resulted in a large die-off of Cladophora and a rapid growth period for P. pectinatus in late July.

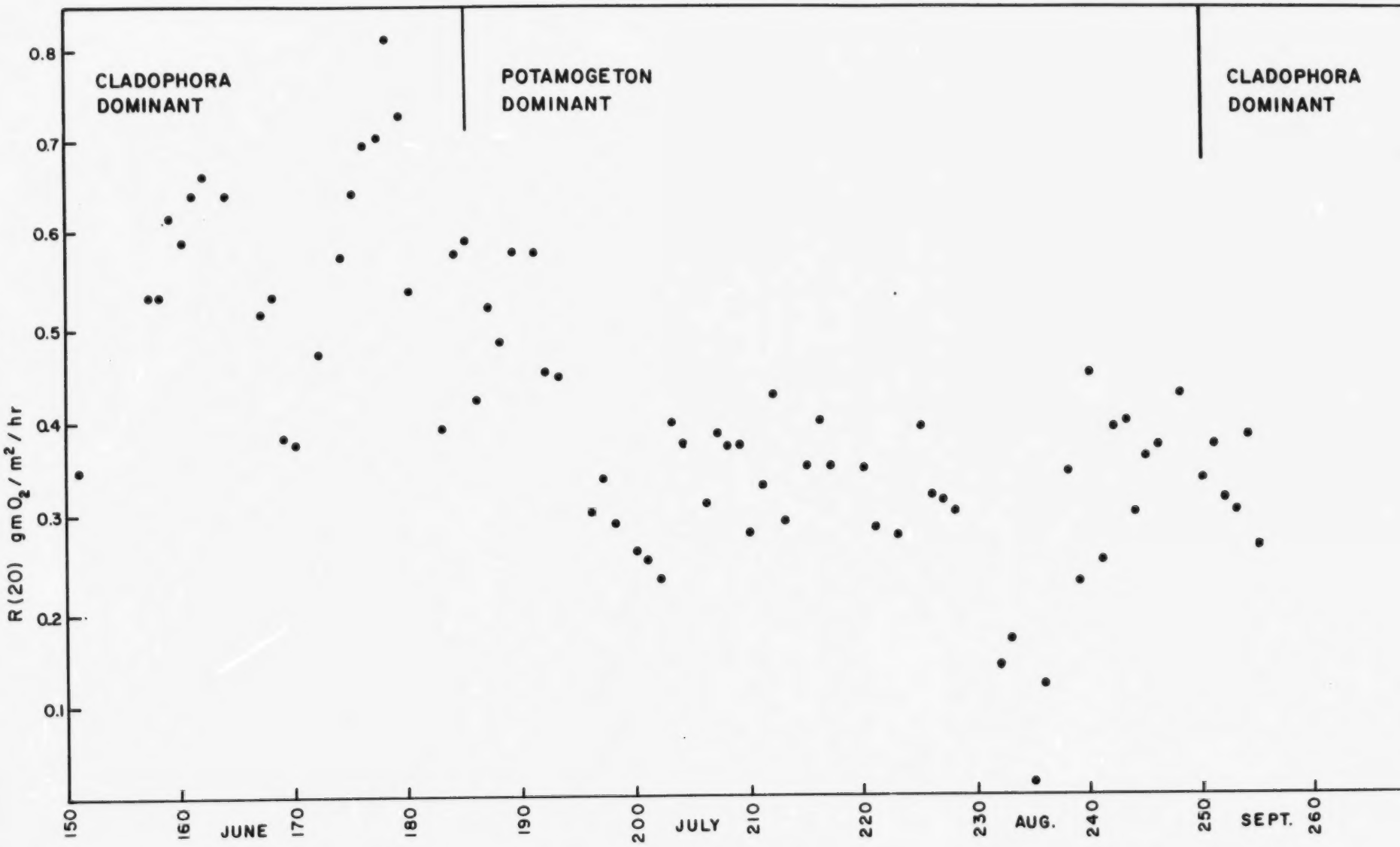


FIGURE 24 SEASONAL COMMUNITY RESPIRATION RATES OBSERVED IN THE GRAND RIVER STUDY REACH.

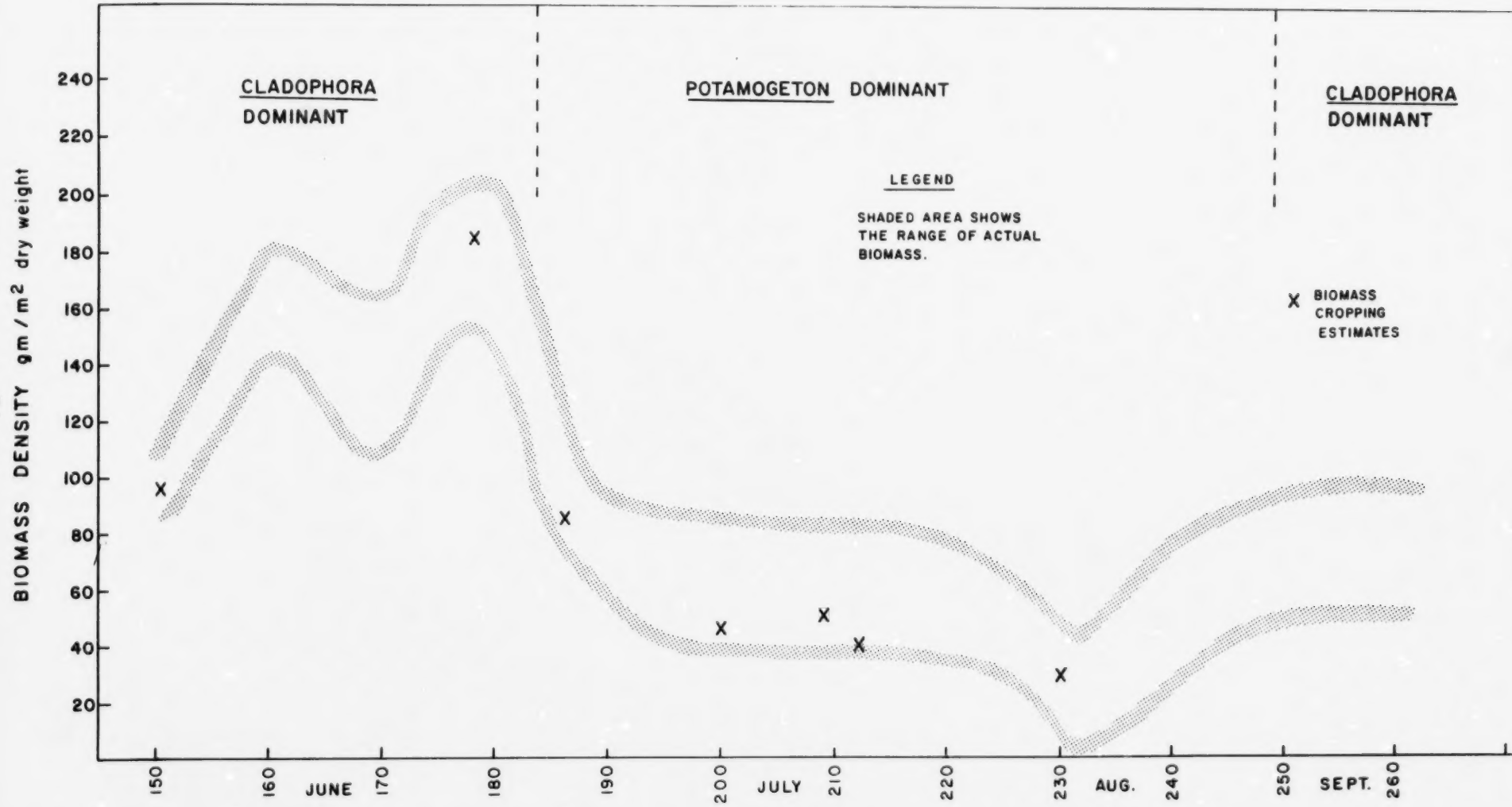


FIGURE 25 ESTIMATED BIOMASS DENSITY IN THE GRAND RIVER STUDY REACH IN 1978.

P. pectinatus dominated the plant community until early September, at which time Cladophora began to reappear in significant quantities. Note that the biomass density in the Speed River exceeded 400 gm/m^2 for most of the growing season, a very high density, while the biomass density in the Grand River reach never exceeded 250 gm/m^2.

These seasonal curves provided insight into temperature-related trends for plant species, and were used in calibrating the model and in evaluating the model's long-term performance.

4.5 Conceptual Model

Figure 27 illustrates a conceptual version of the biomass model. The attached biomass in a river reach is divided into three groups with a single concentration of stored phosphorus. Plants respire continuously resulting in the release of soluble nutrients to the stream at a rate R1 and the uptake of oxygen from the stream at a rate R4. These transfer rates are dependent on stream water temperature (T) and oxygen concentration (O_2). As sunlight intensity (I) increases in the early hours of a day, photosynthesis increases resulting in the uptake of soluble nutrients from the stream at a rate R2 and R3, and the production of oxygen in the stream. These rates are governed by T, nutrient supply (N), both N and P, and the photosynthetically available radiation at the plant depth (PARD). Inflow and outflow of soluble nutrients and oxygen to and from the reach account for rates R5, R6, R7 and R8. These exchanges are dependent on flow rate (Q) and the concentrations of nutrients and oxygen entering and leaving the reach. R9 is the input into or release of oxygen from the stream, driven by diffusion and a deviation in O_2 concentration from saturation. The reaeration rate is also related to turbulence and can be shown to relate to flow rate. Finally, the biomass can be gradually or drastically reduced by death and subsequent washout resulting from extreme streamflows and temperatures; these losses are combined as one loss rate, R10.

In all, these ten rates directly or indirectly affect the biomass concentration which, as a result, is in constant dynamic change in the stream.

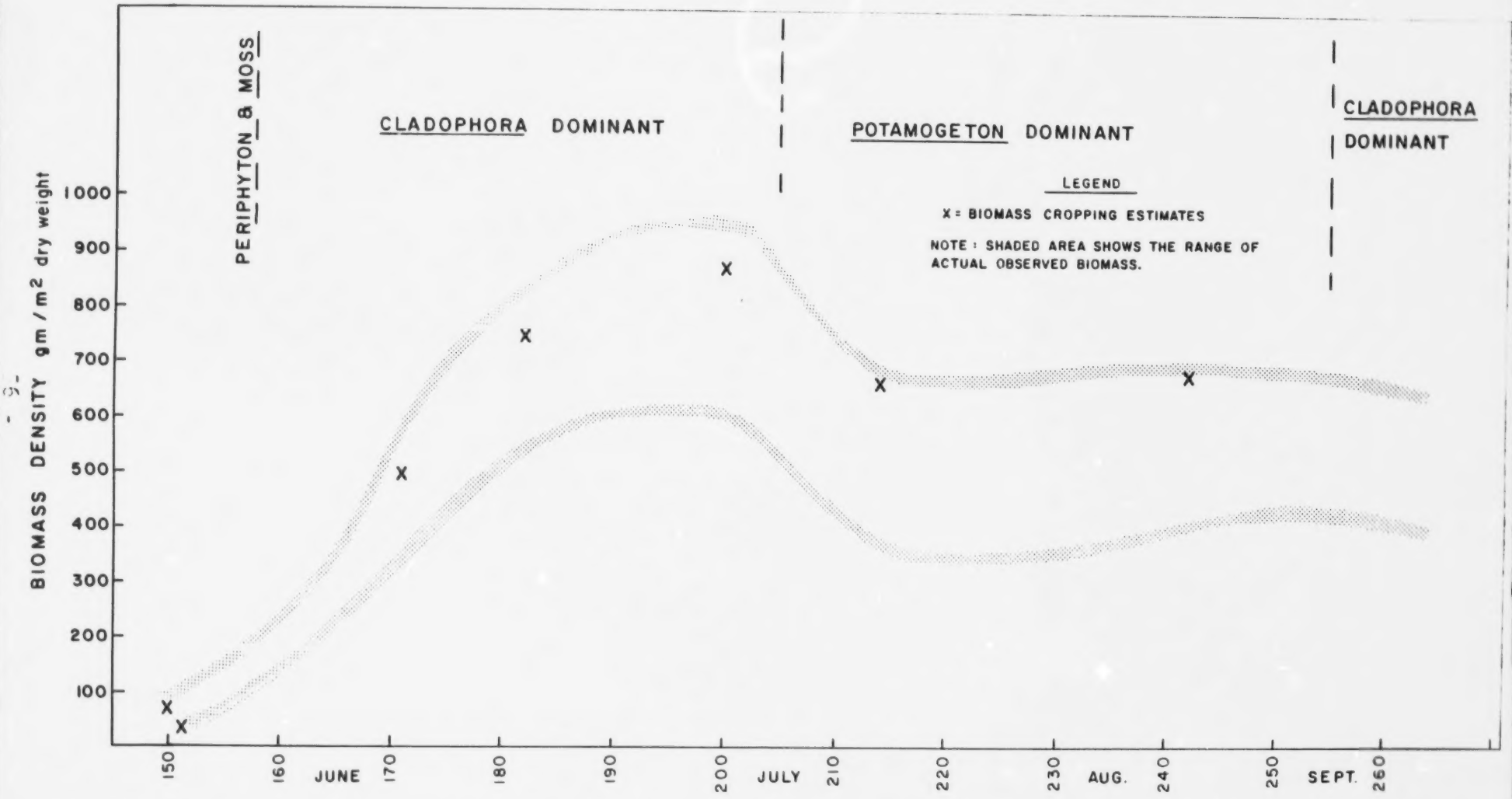


FIGURE 26 ESTIMATED BIOMASS DENSITY IN THE SPEED RIVER STUDY REACH IN 1978.

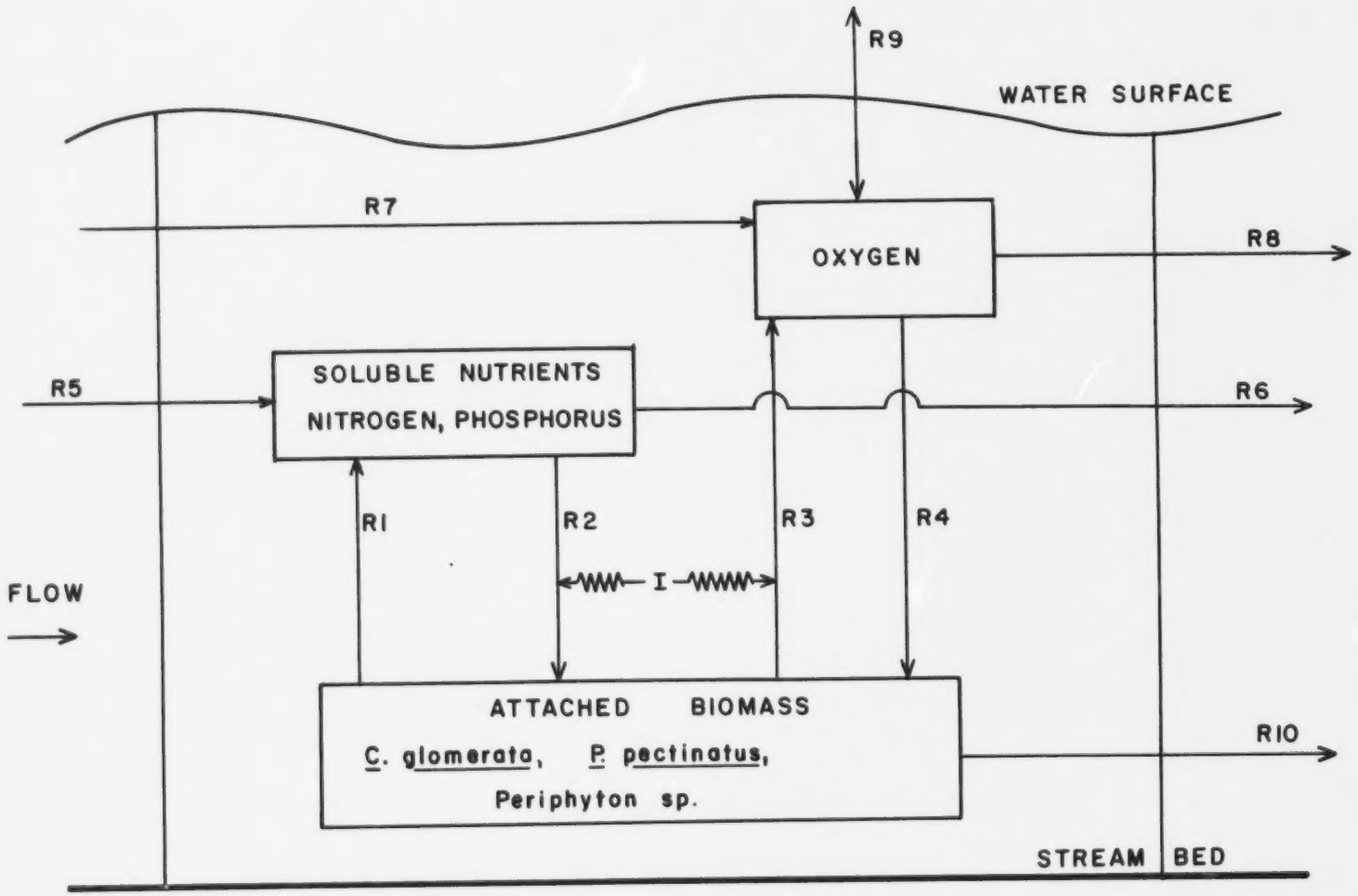


FIGURE 27: CONCEPTIONAL VIEW OF THE BIOMASS MODEL.

CONCEPTUAL MODEL RATES

R1 - Respiratory release rate of soluble nutrients f(T, O_2).

R2 - Photosynthetic uptake rate of soluble nutrients driven by light, f(T,N,PARD)

R3 - Photosynthetic production of oxygen driven by light, f(T,N,PARD)

R4 - Respiratory uptake rate of oxygen, f(T, O_2).

R5 - Inflow of soluble nutrients, f(Q,N)

R6 - Outflow of soluble nutrients, f(Q,N)

R7 - Inflow of oxygen, f(Q,O_2)

R8 - Outflow of oxygen, f(Q,O_2)

R9 - Aeration or deaeration, f(Q,O_2)

R10 - Death and Washout of biomass, f(T)

T - Temperature (^oC)

O_2 - Dissolved Oxygen (mg/L)

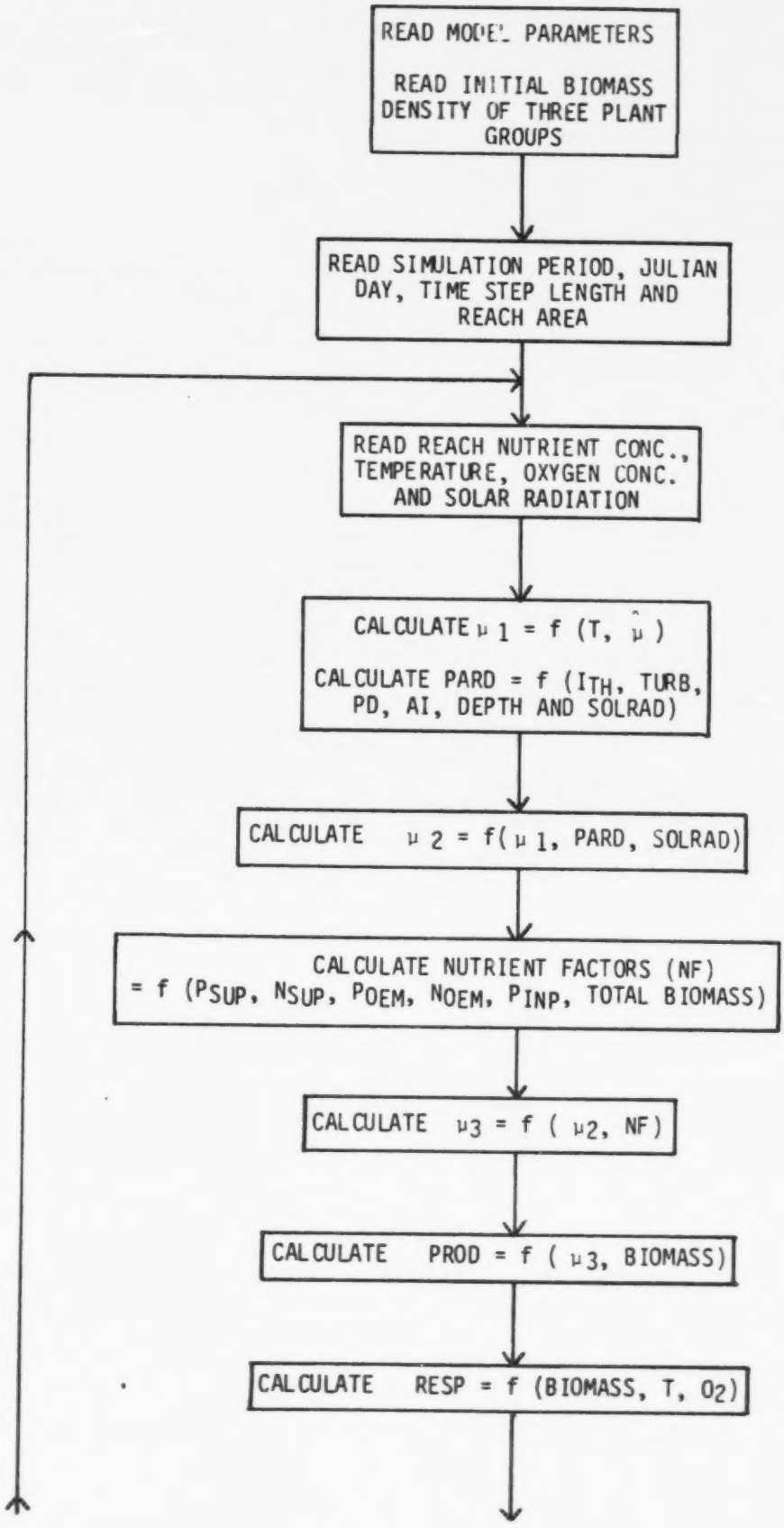
N - Nutrient supply of Phosphorus and Nitrogen

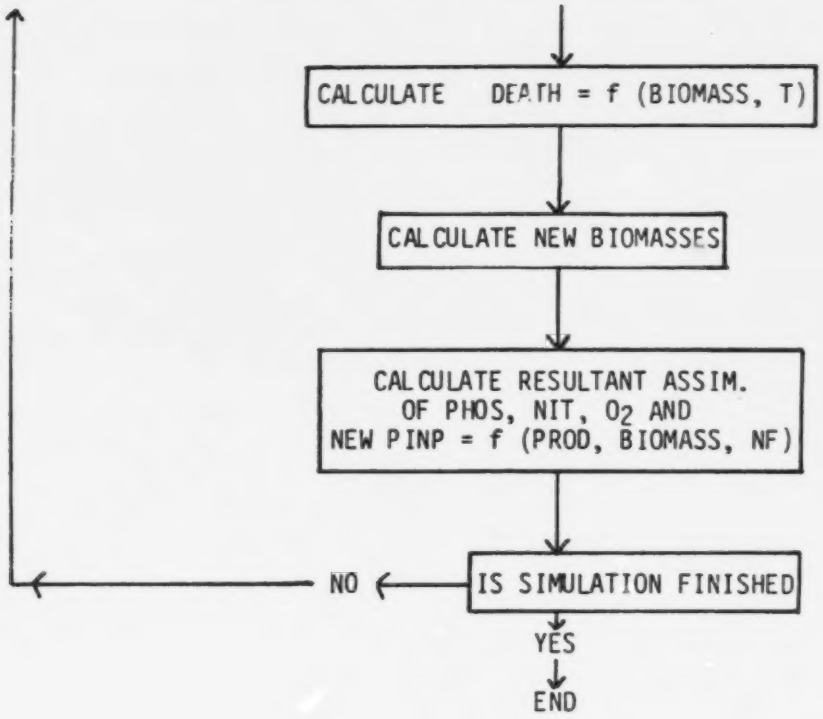
PARD - Photosynthetically Available Radiation at Plant Depth (Langleys/hr)

Q - Stream flow (m^3/sec)

4.6 Flowchart

The following flowchart is a simplified version of the normal progression of operations involved in biomass simulation. The figure is self-explanatory but can be divided into four basic parts. In the first, model parameters, similation directions and initial conditions are established. The second part involves the determination of the degrees of limitations to ideal photosynthesis and respiration which should be applied. In the third part the rates of production, respiration and death-washout are calculated for the time step and are a result of an assemblage of the inhibitions calculated in part 2. The final part is an account of the effects on the nutrient and oxygen budgets in the stream from the biological activity. The computer model, is termed ECOL1 and is written in FORTRAN. A documentation of the program is presented in a separate report (Walker, 1980)


READ MODEL PARAMETERS
READ INITIAL BIOMASS DENSITY OF THREE PLANT GROUPS
READ SIMULATION PERIOD, JULIAN DAY, TIME STEP LENGTH AND REACH AREA
READ REACH NUTRIENT CONC., TEMPERATURE, OXYGEN CONC. AND SOLAR RADIATION
CALCULATE μ 1 = f (T, μ̂)
CALCULATE PARD = f (ITH, TURB, PD, AI, DEPTH AND SOLRAD)
CALCULATE μ 2 = f(μ 1, PARD, SOLRAD)
CALCULATE NUTRIENT FACTORS (NF) = f (PSUP, NSUP, POEM, NOEM, PINP, TOTAL BIOMASS)
CALCULATE μ3 = f (μ2, NF)
CALCULATE PROD = f (μ3, BIOMASS)
CALCULATE RESP = f (BIOMASS, T, O2)


CALCULATE DEATH = f (BIOMASS, T)
CALCULATE NEW BIOMASSES
CALCULATE RESULTANT ASSIM.
OF PHOS, NIT, O_2 AND
NEW PINP = f (PROD, BIOMASS, NF)
IS SIMULATION FINISHED
NO
YES
END

5. MODEL TESTING

5.1 Introduction

The procedure of model testing and the results of testing ECOL1 are discussed in this chapter. Model testing involves sensitivity analysis to assess the individual submodels within the model, calibration to refine the model parameters and verification to confirm the model's usefulness in independent applications.

5.2 Sensitivity Analysis

A sensitivity analysis is done to aid calibration and to improve one's understanding of a model. With the aid of a computer, several simulations can be made in which major submodel parameters are varied within acceptable limits. The result of each parameter change can then be examined in the context of the whole model. Those parameters which appear to have a large effect on the simulation results should then receive the largest amount of attention when selecting final model input values. This kind of information can also assist in the design of data collection programs aimed at measuring model parameters.

Extensive sensitivity analyses were conducted on ECOL1 in the model development and calibration process and no attempt is made here to present the comprehensive results. However, examples are presented which illustrate the type of information derived in this manner. All examples shown were derived from an application to the Grand River study reach during the beginning of the growth period (ie., June).

Five aspects of ECOL1 are tested, namely: radiation, growth, respiration, temperature and nutrients. The radiation model parameter K_I (Equation 22) was varied and model runs being made at values of 0.5, 0.75 and 1.0 langleys/hr. Figure 28 illustrates the different biomass densities simulated with the three values. It is apparent from this that the entire model is sensitive to this

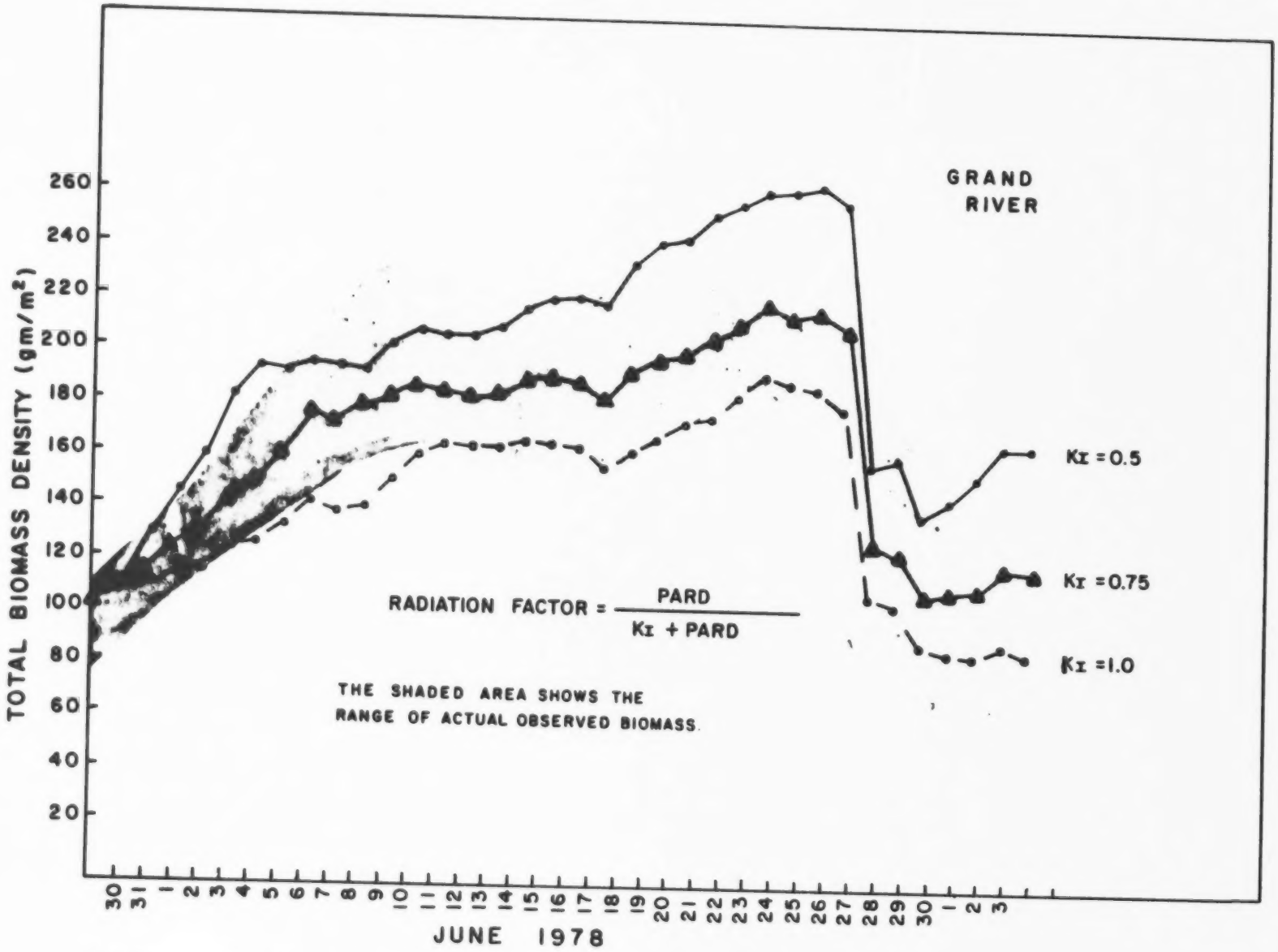


FIGURE 28 SENSITIVITY OF BIOMASS PRODUCTION TO K_I.

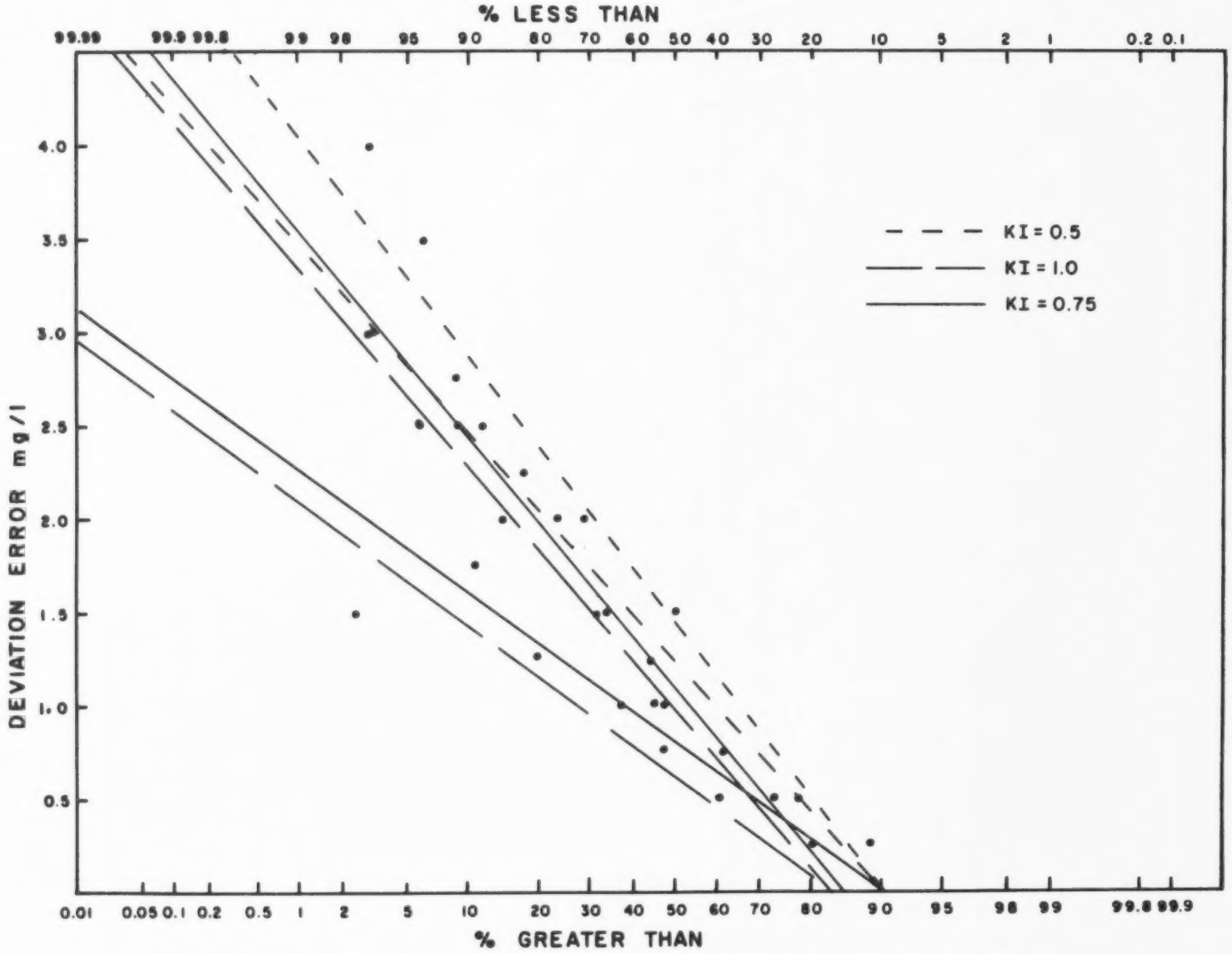


FIGURE 29 ERROR ANALYSIS OF SENSITIVITY ANALYSIS WITH VARIOUS VALUES OF KI.

one parameter and its value should be carefully chosen in the end. Figure 29 illustrates the differences achieved in terms of the model's ability to predict daily observed maximum and minimum dissolved oxygen concentrations. These results indicate that the run with K_I equal to 0.5 was worse in this respect than the other two runs.

Figures 30 and 31 similarly represent the results of sensitivity and error analyses in which the specific maximum growth rate of Cladophora (the dominant species at the time), $\hat{\mu}_{cg}$, is varied. Naturally, growth and biomass density are higher in the last case; however the biomass densities attained are somewhat less than double those achieved with $\hat{\mu}_{cg}$ equal to 0.06. Obviously, other model considerations tend to buffer this parameter. Oxygen concentration predictions (Fig. 31) are similar when $\hat{\mu}_{cg}$ equals 0.06 or 0.087.

When the unit respiration rate of Cladophora, R(20), is varied from 0.0015 to 0.0045 gm O_2/gm-hr, large differences result in biomass density (Fig. 32). These results are not reflected in terms of oxygen concentration predictions as indicated by the error analysis (Fig. 33). In fact, Figure 33 indicates that no significant difference exists. This is due to the fact that the lower biomass densities predicted by a high R(20) are balanced by a larger unit respiration rate and subsequent greater depletion of the stream's oxygen.

The value θ in the temperature correction equation (equation 24) was varied from 1.05 to 1.20 and resultant simulation results appear in Figures 34 and 35. This parameter had a relatively small effect on the results during most of the period studied, largely due to the fact that stream temperatures fluctuated near 20°C during much of this period. This sub-model only becomes important at extreme summertime temperatures.

The nutrient efficiency factor REQFAC (Equation 32) was varied from 1.2 to 3.5 in this analysis. Results presented in Figures 36 and 37 indicate that the model is sensitive to this parameter. When

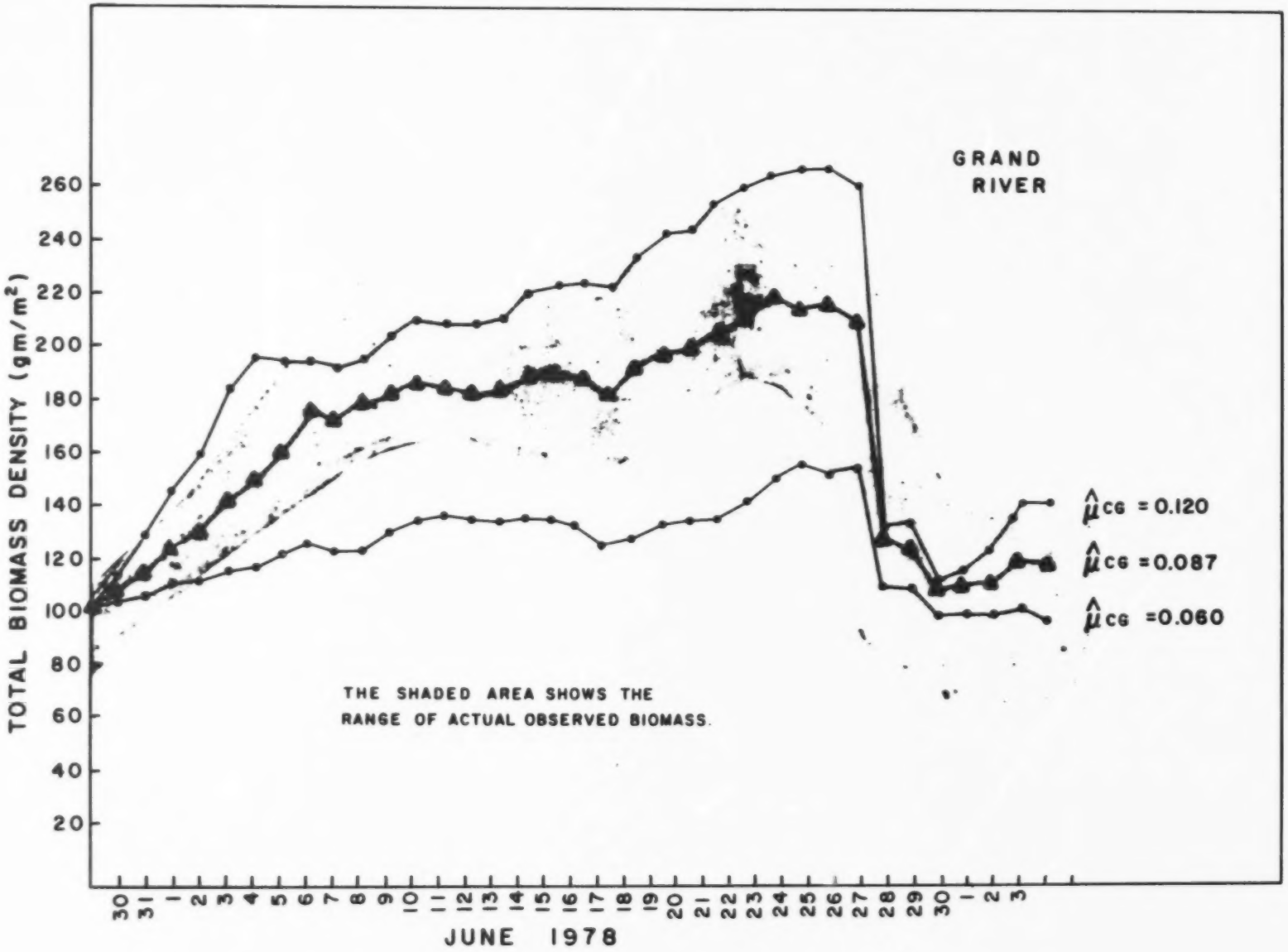


FIGURE 30 SENSITIVITY OF BIOMASS PRODUCTION TO $\hat{\mu}$.

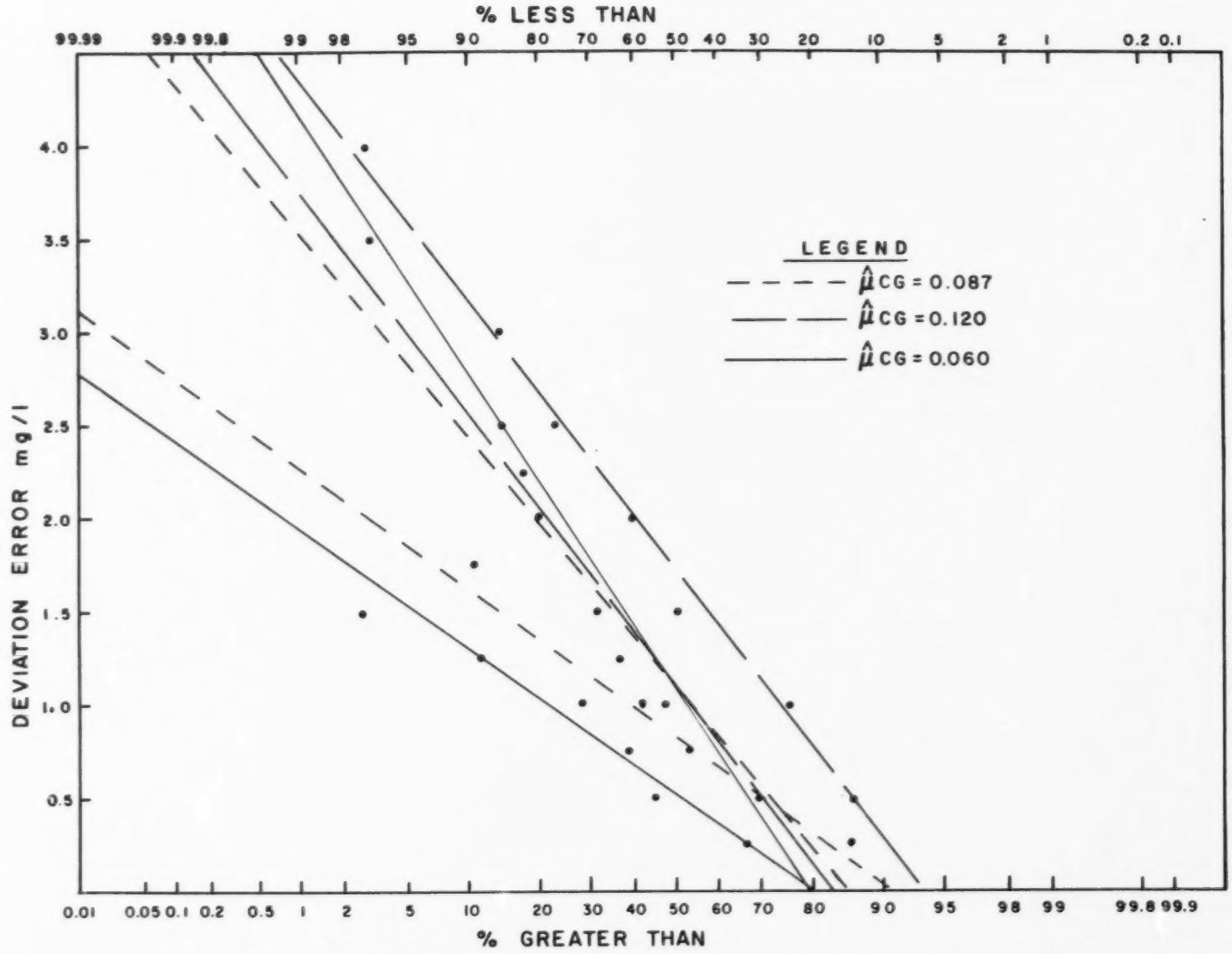


FIGURE 31 ERROR ANALYSIS OF SENSITIVITY ANALYSIS WITH VARIOUS VALUES OF $\hat{\mu}$.

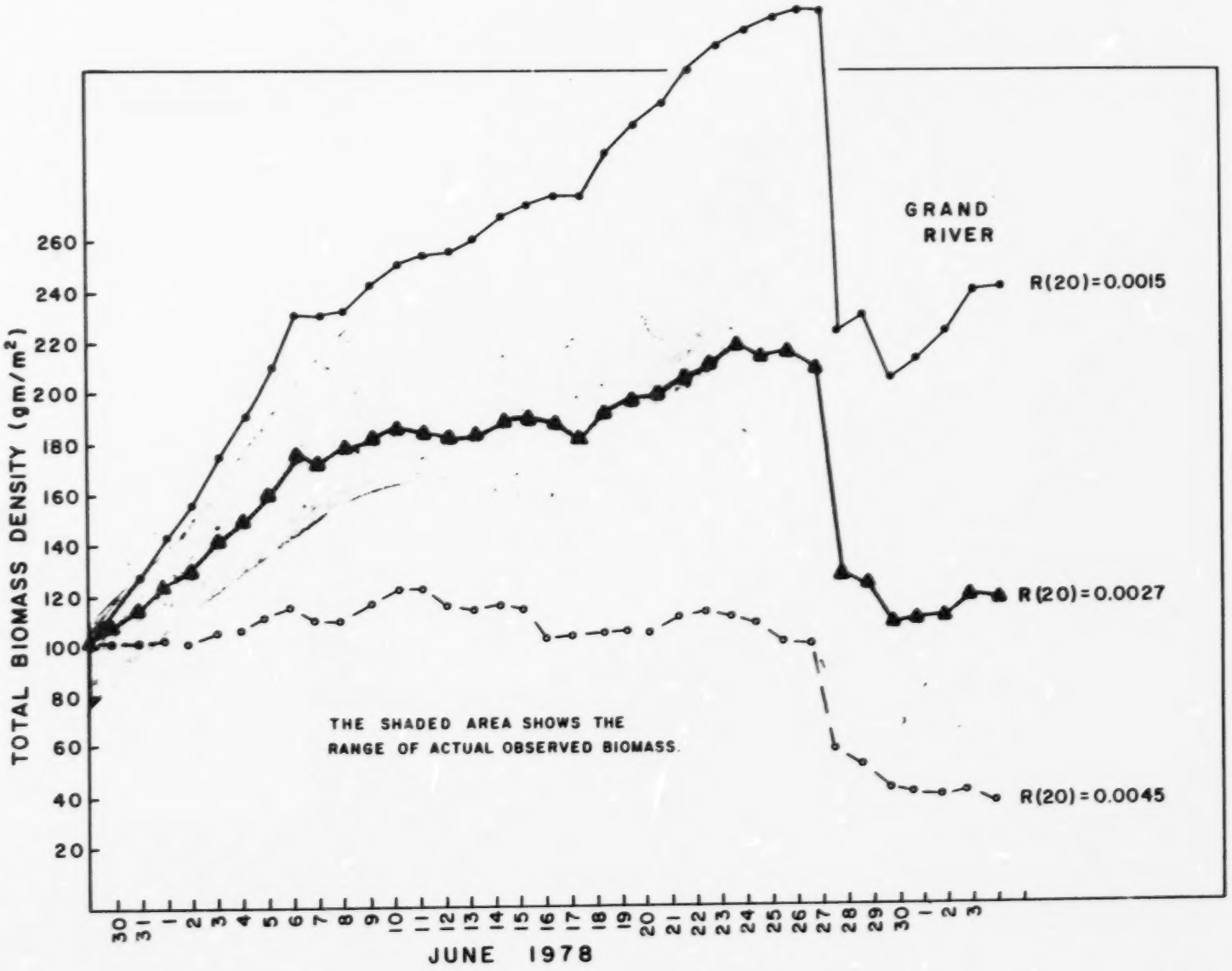


FIGURE 32 SENSITIVITY OF BIOMASS PRODUCTION TO R(20).

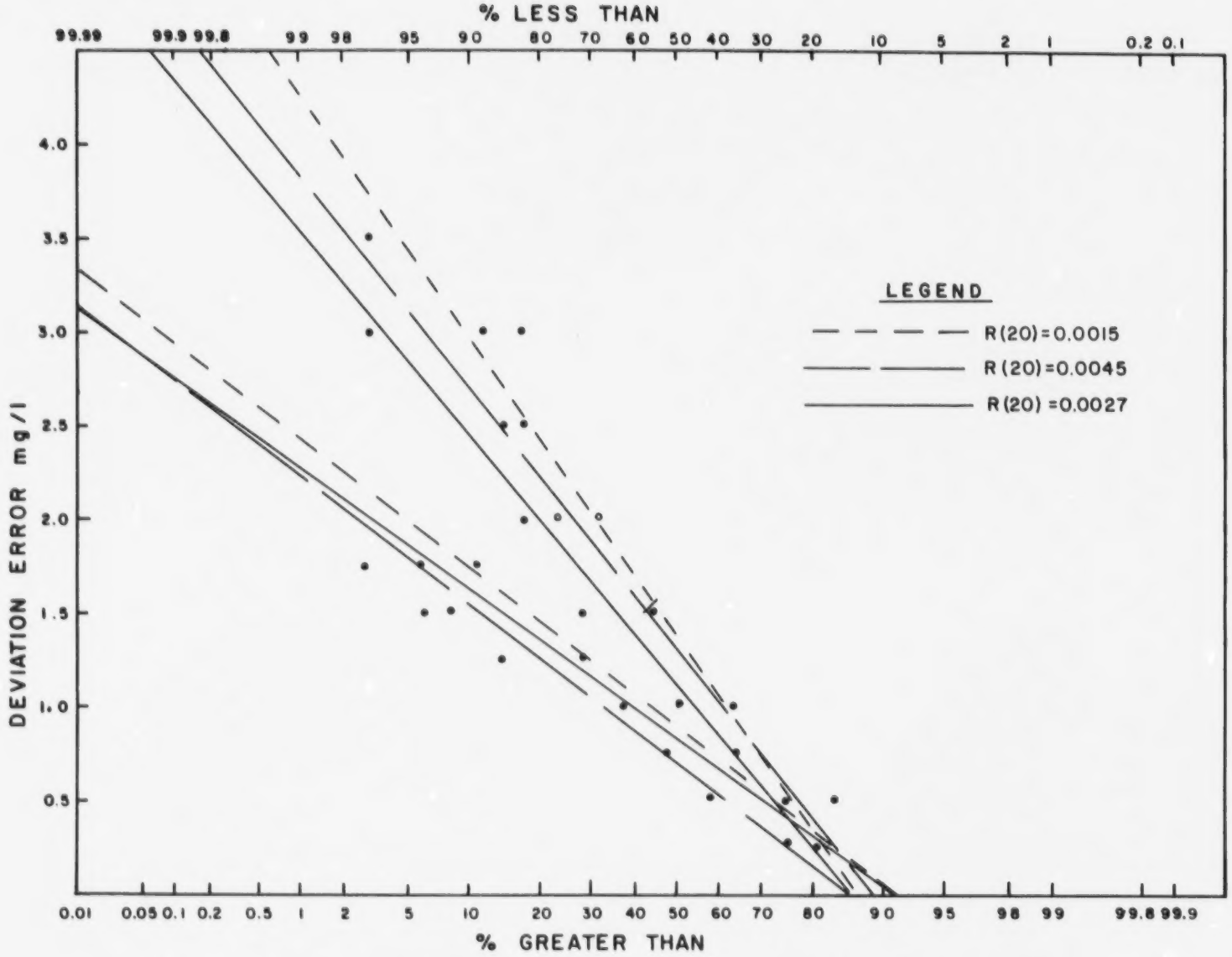


FIGURE 33 ERROR ANALYSIS OF SENSITIVITY ANALYSIS WITH VARIOUS VALUES OF R(20).

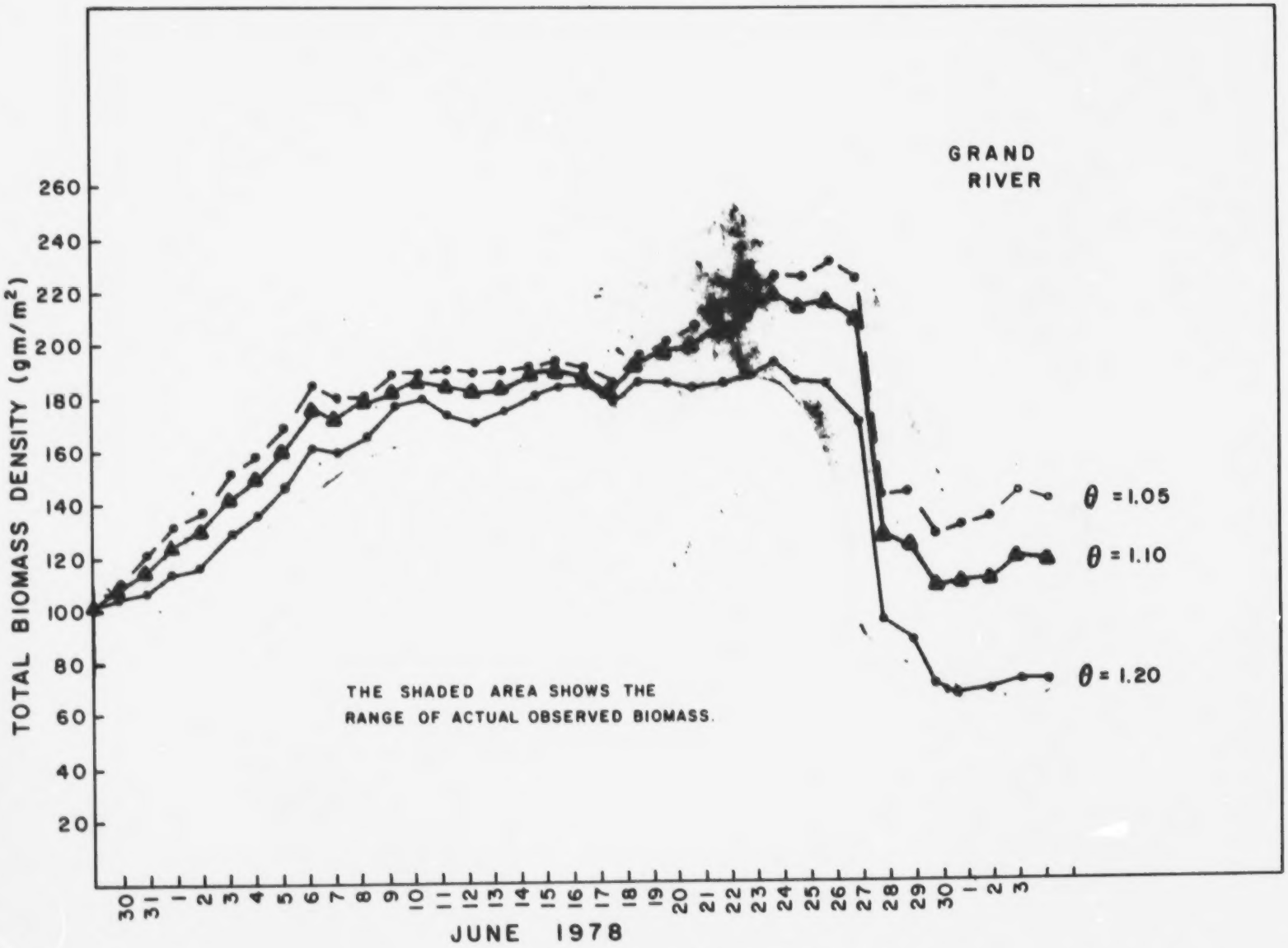


FIGURE 34 SENSITIVITY OF BIOMASS PRODUCTION TO θ.

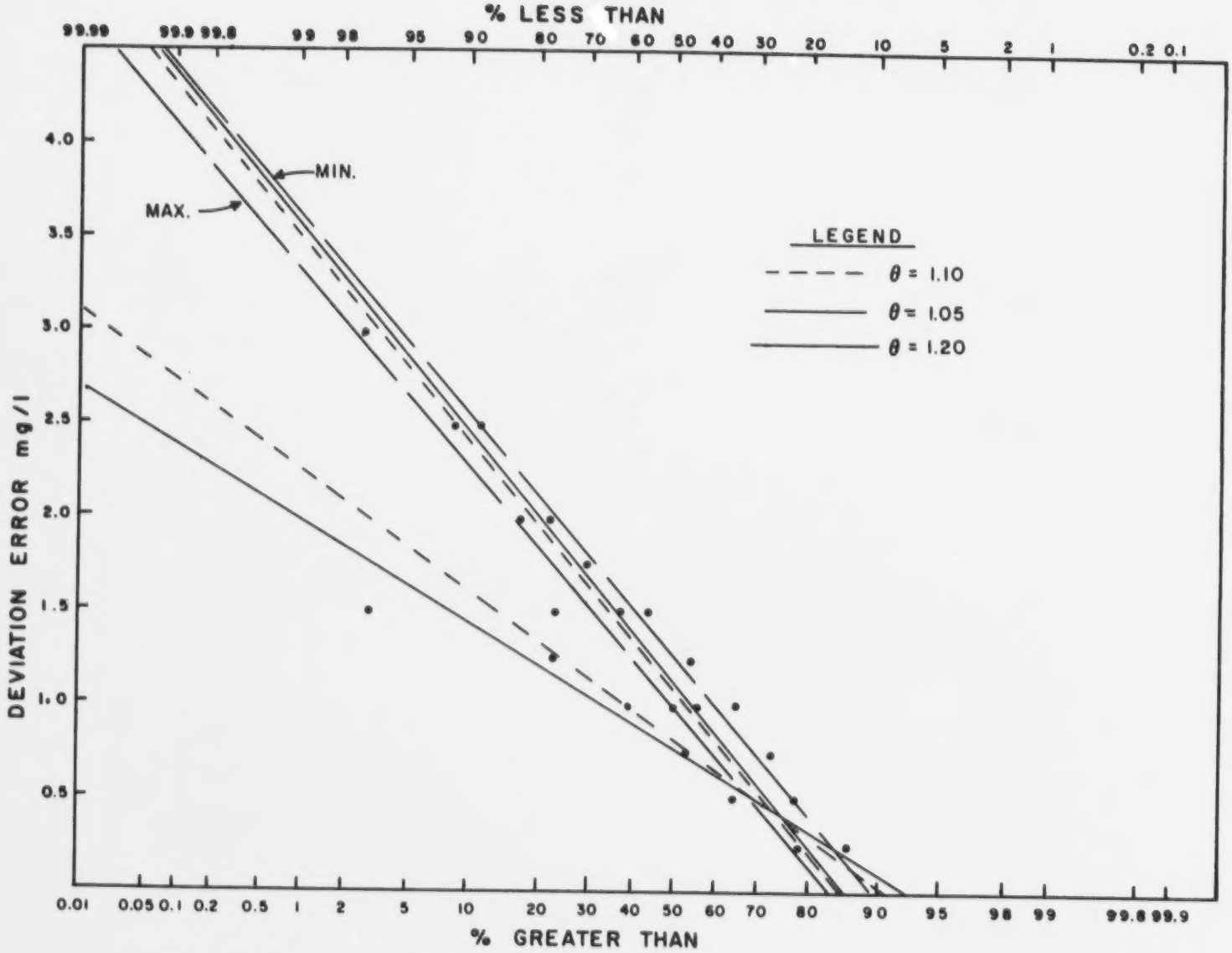


FIGURE 35 ERROR ANALYSIS OF SENSITIVITY ANALYSIS WITH VARIOUS VALUES OF θ.

REQFAC equals 1.2, the biomass is very efficient at nutrient removal from the water and a high biomass density results. Oxygen concentration prediction error analysis (Fig. 37) however indicates that this scenario results in poor prediction accuracy.

The foregoing results of the sensitivity analysis indicate that K_I, R(20) and REQFAC are particularly important parameters and care must be exercised when calibrating the submodels in which they are involved. The parameters $\hat{\mu}cg$ and θ are of somewhat less importance but can be more so under certain conditions. Many other model parameters displayed low levels of sensitivity in this analysis and hence have not been described.

5.3. Calibration

Calibration is the process by which the parameters of the individual component submodels in a model are refined and selected. The data set chosen should be typical, but also display a degree of variability so that the various submodels are well tested. In this exercise the Grand River study reach data from 1978 were used in calibration. These data represented a phosphorus limited system, thus allowing for calibration of the nutrient submodels.

The model, ECOL1, contains a relatively large number of parameters necessitating a highly ordered approach. Calibration proceeded in the following manner:

- initial biomass was estimated and species unit respiration rates R(20) adjusted to reflect the observed daily minimum DO oxygen concentrations, the latter being unaffected by radiation or plant growth rate in the short term.

- unit growth rates $\hat{\mu}cg$ were set such that seasonal biomass trends approximated the observed biomass trends.

- washout model parameters were adjusted to reflect washout events and seasonal trends.

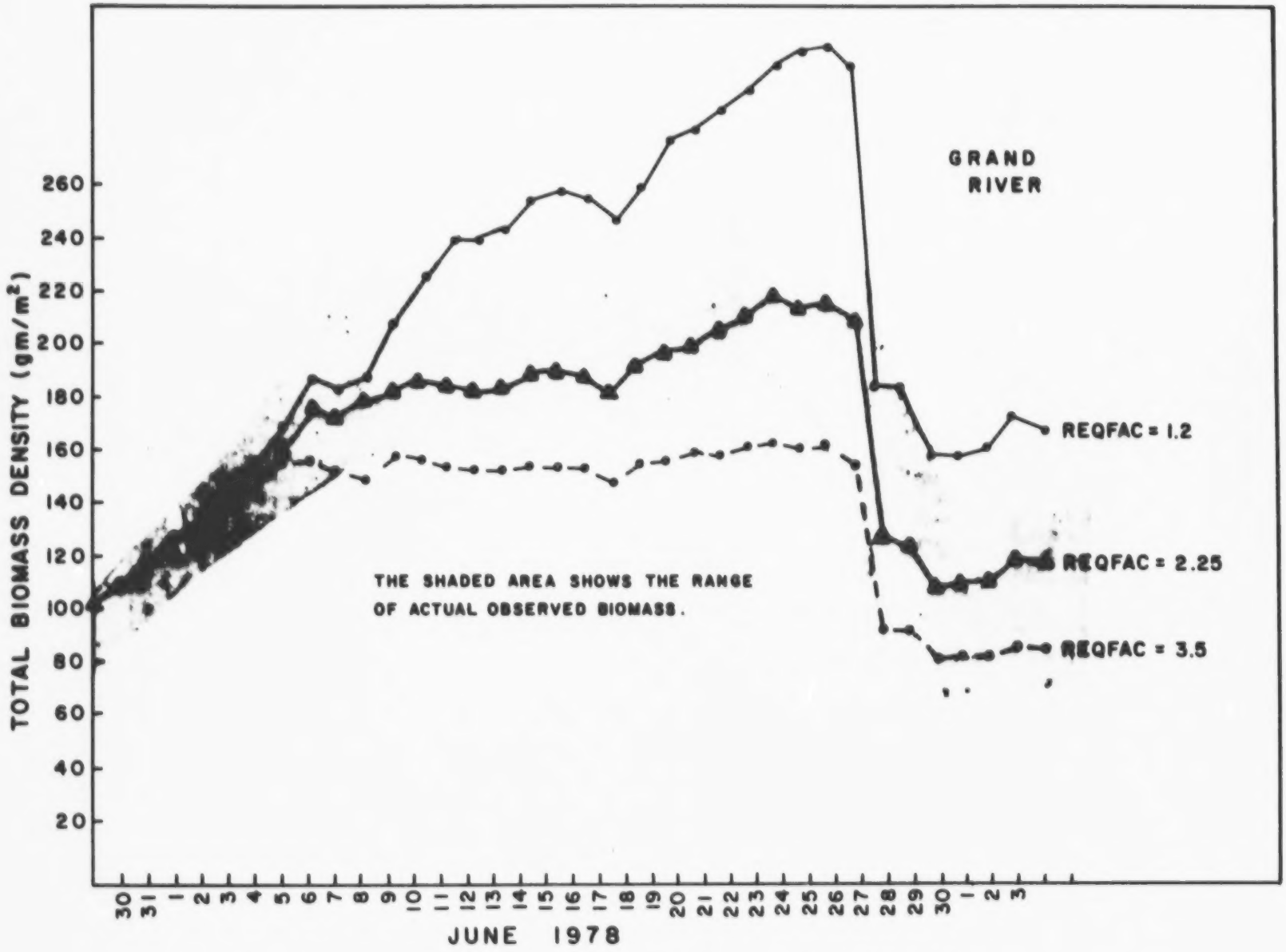


FIGURE 36: SENSITIVITY OF BIOMASS PRODUCTION TO REQFAC.

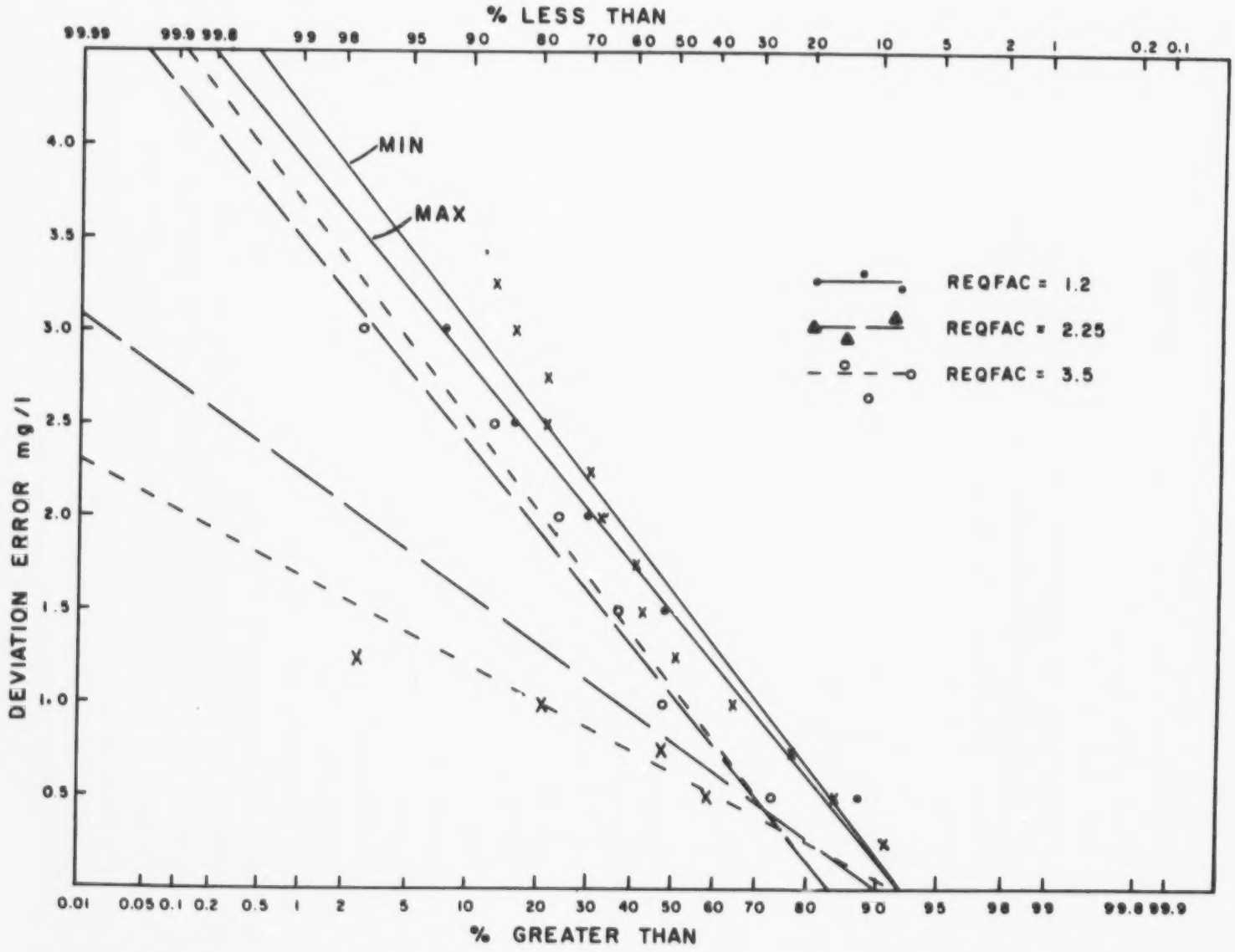


FIGURE 37 ERROR ANALYSIS OF SENSITIVITY ANALYSIS WITH VARIOUS VALUES OF REQFAC.

- radiation model parameters were adjusted to reflect day to day variations in maximum dissolved oxygen.

- nutrient model parameters were adjusted to reflect seasonal phosphorus storage data

- unit growth rates were adjusted to reflect daily maximum D.O. and seasonal trends.

- respiration and temperature model parameters were adjusted to reflect the observations made during a period of drastic temperature change with respect to minimum DO

This process was then repeated at higher degrees of refinement until model results were in close agreement with the observations in terms of D.O. and seasonal biomass trends.

Cladophora and P. pectinatus dominate at different times of the year so that the individual model parameters can be refined independently.

The results of calibration in terms of seasonal total biomass are shown in Figure 38. Parameter values and final model form are detailed in the model documentation (Walker, 1980). The actual observed biomass is reported as a range, due to imprecise techniques available for estimating biomass. Figure 39 illustrates the calibration results in terms of errors from daily minimum and maximum observed average D.O. values in the study reach. The percent of deviation error indicates that 50% of the errors in the prediction of daily minimum dissolved oxygen concentrations are less than 0.5 mg/L and 95% of the errors are less than 1.2 mg/L. In terms of daily maximums, 50% of the errors are less than 1.2 mg/L and 95% of the errors are less than 3.2 mg/L. Errors are higher in predicting daily maximums because more factors are involved in predicting these values (solar radiation and nutrient supply), and because daily maximum values are very high (10.5 - 20.0 mg/L). In relative terms these errors are similar for both maximum and minimum values. These results were considered to be quite acceptable and allowed for continued testing by verification.

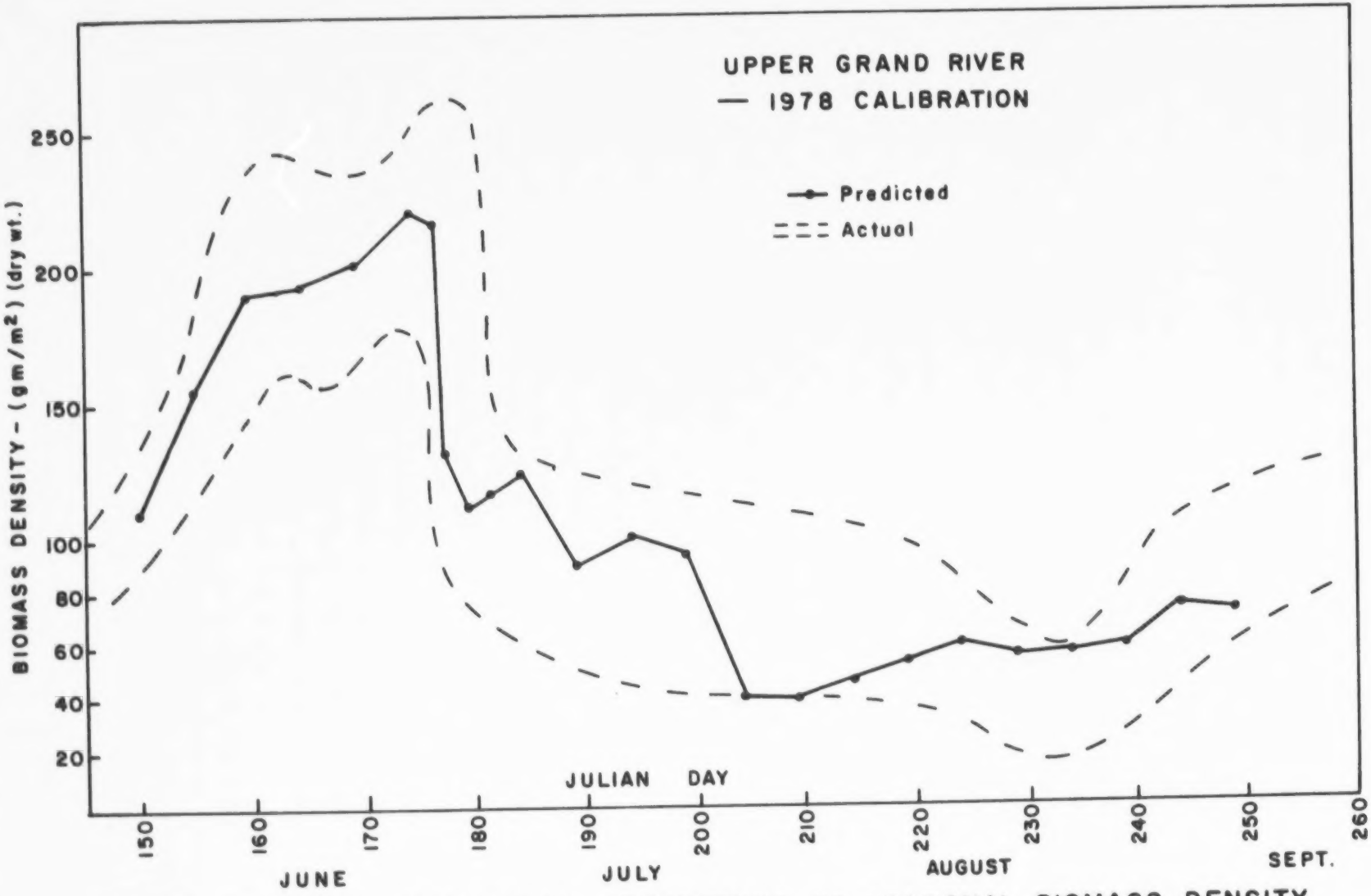


FIGURE 38 FINAL CALIBRATION PREDICTIONS OF SEASONAL BIOMASS DENSITY IN THE GRAND RIVER.

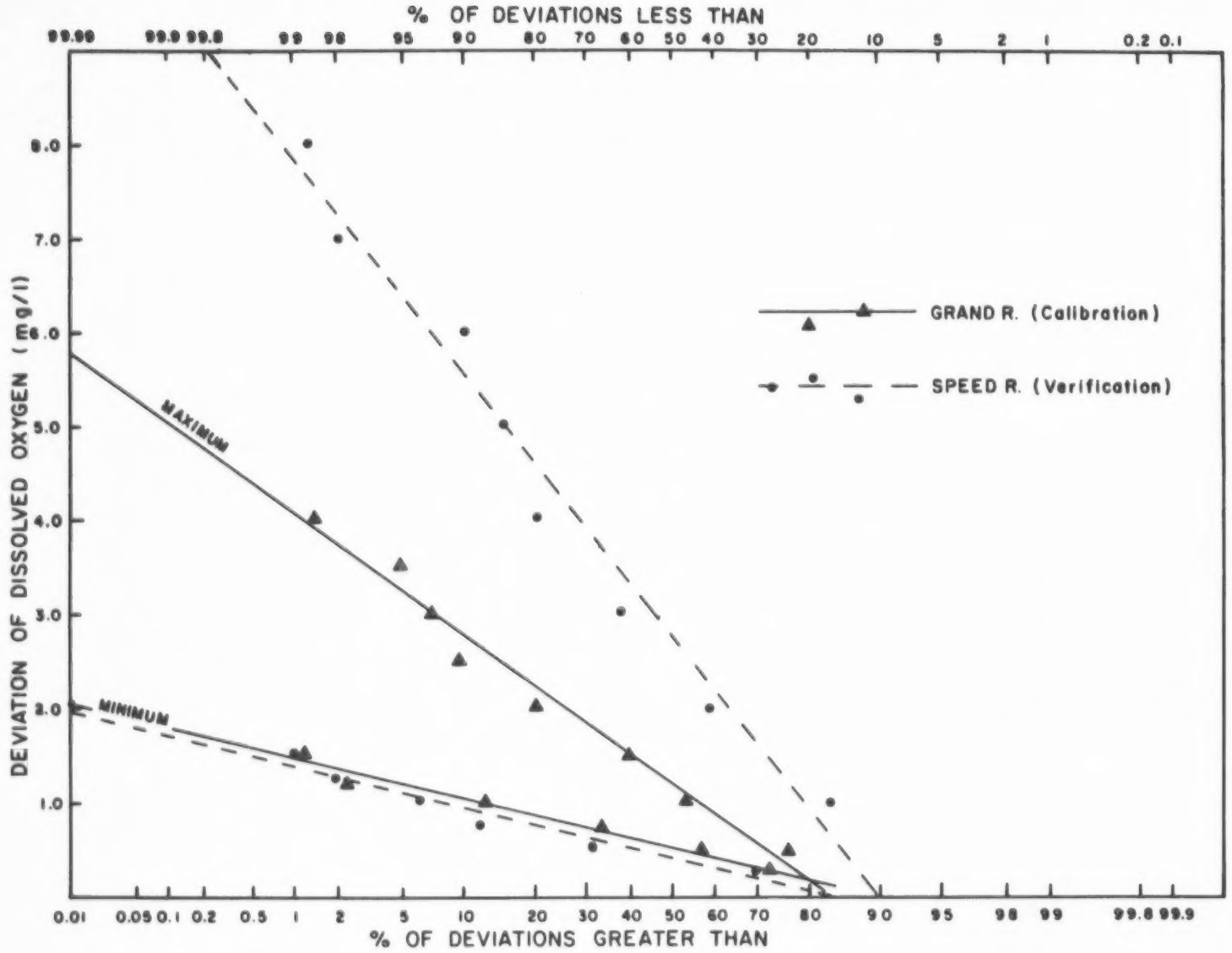

% OF DEVIATIONS LESS THAN
99.99 99.9 99.8 99 98 95 90 80 70 60 50 40 30 20 10 5 2 1 0.2 0.1
DEVIATION OF DISSOLVED OXYGEN (mg/l)
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
MAXIMUM
MINIMUM
GRAND R. (Calibration)
SPEED R. (Verification)
0.01 0.05 0.1 0.2 0.5 1 2 5 10 20 30 40 50 60 70 80 90 95 98 99 99.8 99.9
% OF DEVIATIONS GREATER THAN

FIGURE 39 ERROR ANALYSIS OF DISSOLVED OXYGEN PREDICTION IN CALIBRATION AND VERIFICATION.

5.4 Verification

The process of model testing is complete when an acceptable verification has been performed. This involves testing the model, with its submodel parameters set by calibration, on a different set of data. This new data set should be completely independent of the set used to calibrate the model within the stated limitations of the model. For water quality models, the condition of complete independence of a verification data set is met when the new data set is from a different time period for the same water system or from a different water system. Verification is enhanced when the data sets represent widely different conditions. In this study the Speed River study reach data set from 1978 was used for verification of the model. This reach is completely independent geographically from the Grand River calibration reach in that the rivers do not share head waters. The reach also displays very different water quality conditions and characteristic aquatic plant communities. The Speed River is much more enriched and typically supports an extremely high plant density. This data set provided for a good test of the nutrient and self shading components of the model.

Figure 40 illustrates the predicted and the observed range of total biomass for the Speed River reach in 1978. Predictions are in the lower range of observed values but generally follow the observed trends. Note that observed and predicted total biomass are much higher than that in the Grand River reach throughout the summer months. Figure 39 also shows the results of error analysis of the verification run in terms of maximum and minimum dissolved oxygen prediction. Average reach minimum dissolved oxygen concentrations were predicted to within 0.4 mg/L on 50% of the days and to within 1.1 mg/L on 95% of the days. These results are slightly better than those obtained in the calibration reach. Maximum values were predicted with less success, with 50% of the errors less than 2.7 mg/L and 95% of the errors less than 6.4 mg/L. Estimation errors in this reach are in part due to the complications of additional large bacterial respiratory oxygen demands which interfere with the Odum's method of productivity analysis. The model generally predicted higher maximum values in comparison to the field observations. Discrepancies could also be due to errors in estimating reaeration.

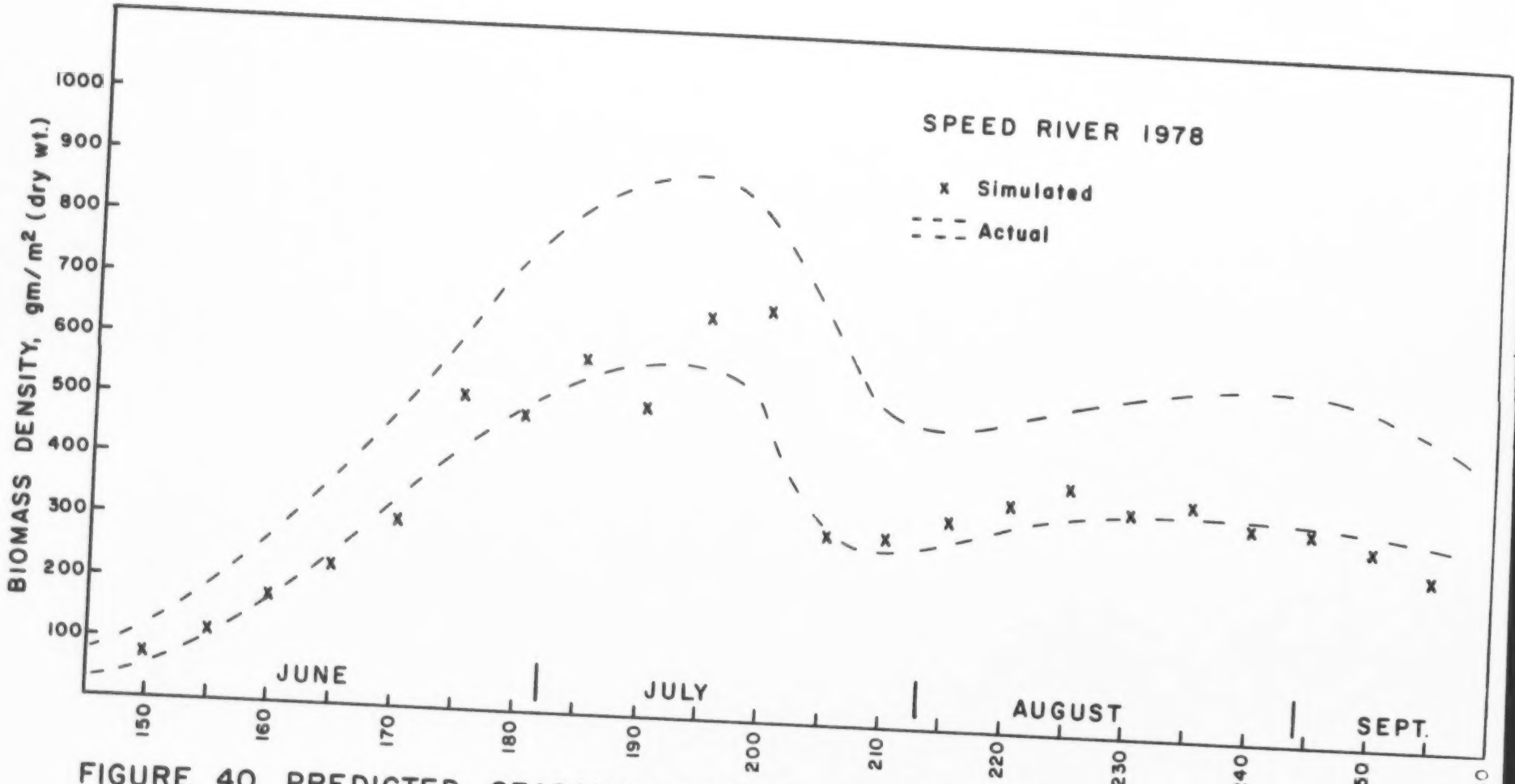


FIGURE 40 PREDICTED SEASONAL BIOMASS DENSITIES IN THE SPEED RIVER FROM VERIFICATION.

These results were considered to be satisfactory and constitute verification of the model. In fact, the process of calibration and verification often is a feedback process, which was indeed the case in this study. That is, if verification is unsatisfactory then re-calibration and re-verification must take place.

6.0 APPLICATIONS

The ECOL1 model accounts for the effects of the major environmental parameters (stream temperature, nutrients and solar conditions) on plant growth. It is therefore possible to evaluate short- and long-term effects for a wide range of management options in a river basin management program. A model version was created which has the capability to model oxygen concentration and hydraulic parameters. This version was also used in calibration and verification (see Sections 5.3 and 5.4). To demonstrate the model's usefulness three stream improvement options were simulated for the Grand River study reach. These options involve flow augmentation, nutrient control and instream removal of plants; the simulations are compared for the critical June period in 1978.

Flow augmentation is a common management option, requiring the construction of expensive water reservoirs and used primarily for increasing a stream's waste assimilative capacity during low flow periods. Plant growth is not directly related to stream flow rate, provided that conditions of stream velocity, depth and turbidity remain suitable. The major effects of flow augmentation in ECOL1 are to increase stream depth and thus reduce PARD, to increase the nutrient flux and to reduce the reaeration coefficient. These effects have opposite results, and to identify the net effect a simulation was conducted in which flow rates were not allowed to decrease below 7.0 m^3/s in the month of June in the Grand River reach. Flows were observed to decrease to 3.7 m^3/s in this reach in June 1978. If the reservoir which supplied these augmenting flows was a short distance upstream of this reach then nutrient flux in the reach would have a relatively constant rate. Therefore, in this simulation, filtered phosphorus concentrations were held at 0.03 mg/L, a typical concentration in the existing Grand River Basin reservoirs.

Nutrient reduction is a common management strategy and, as an example, a simulation was made in which filtered phosphorus flux in the stream was reduced by one third. This could be the result of a significant improvement in point and non-point source nutrient control. The reduced phosphorus levels used here are only slightly above background levels in the upper middle Grand River Basin.

Instream plant removal has been considered as a temporary remedial measure which recognizes the periodicity of aquatic plant density and takes advantage of this. It is possible with close monitoring to predict the point in time at which a weed bed will have achieved a 'problem density' and at this time to physically reduce the plant biomass in the stream. A simulation was performed in which the dominant Cladophora was removed from the reach when the biomass exceeded 150 gm/m^2. For practical reasons the biomass density was step-changed down to 10 gm/m^2 of Cladophora. The other species' densities remained unchanged. This removal constituted a harvest of about 25 metric tons of dry plant material from the 2 mile reach.

The results of these simulations in terms of biomass density appear in Figure 41. Biomass cropping was obviously effective in reducing biomass density for the period of simulation. The growth of other species in the absence of Cladophora would eventually result in a similar biomass in July without cropping. Nutrient reduction results in stalling the biomass increase at about 150 gm/m^2. During this period the simulated biomass remains in a nutrient limited condition. Flow augmentation results in a large increase in biomass in late June. This is due to the higher nutrient flux supplied during peak productivity hours. Under actual conditions in this reach, afternoon nutrient concentrations were often depressed due to assimilation by upstream weedbeds. The simulation result shown here is largely due to nutrient supply. Higher flow rates and greater mean depths do not significantly reduce modelled growth.

Figure 42 illustrates the daily dissolved oxygen distributions which were simulated by the three management scenarios outlined. The cropping scenario clearly is the most effective and results in a minimum number of violations at the 4 mg/L level. Nutrient reduction is also effective yet, the 4 mg/L level is violated during

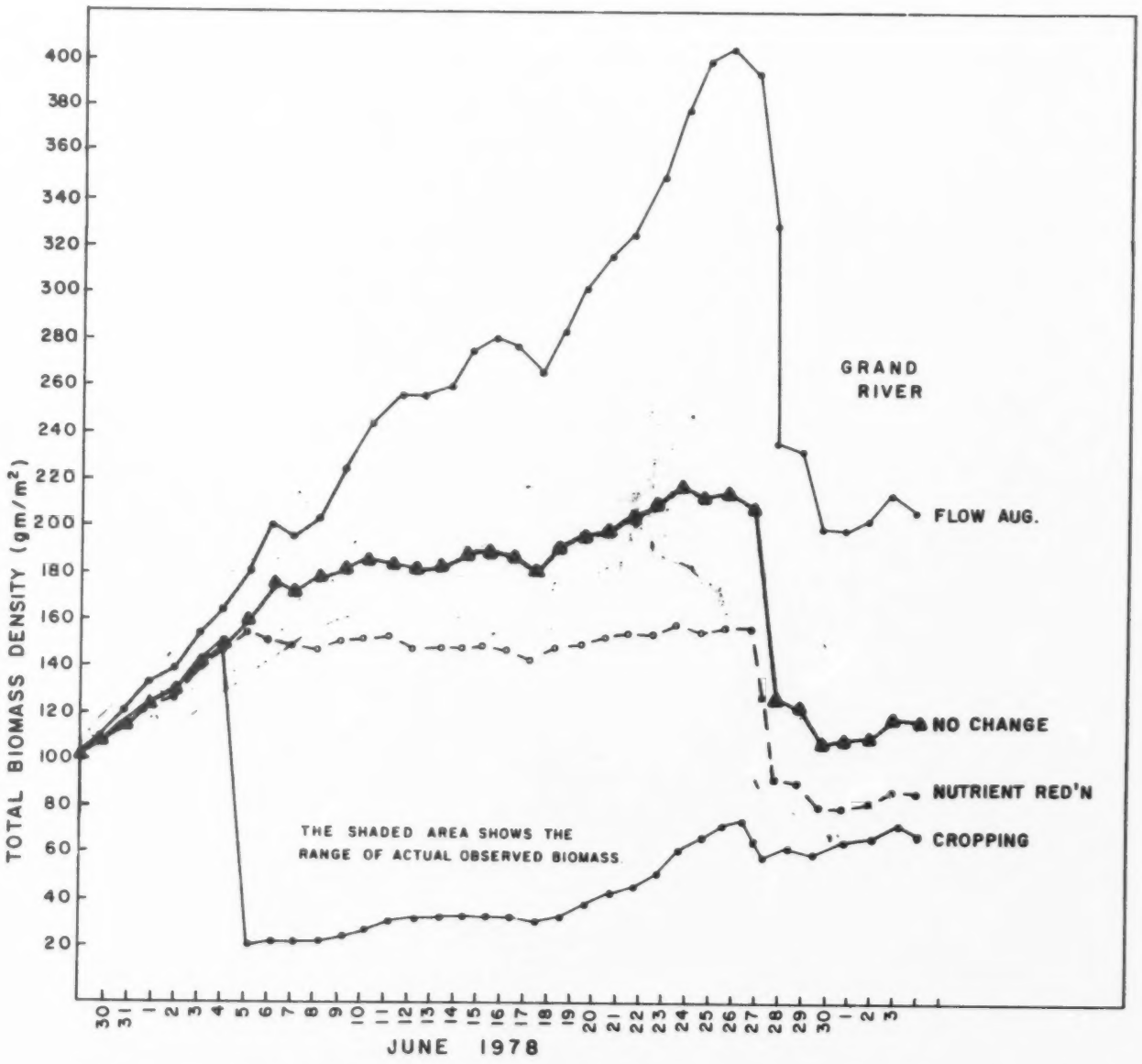


FIGURE 41 SEASONAL BIOMASS TRENDS FROM SIMULATIONS WITH MANAGEMENT SCENARIOS.

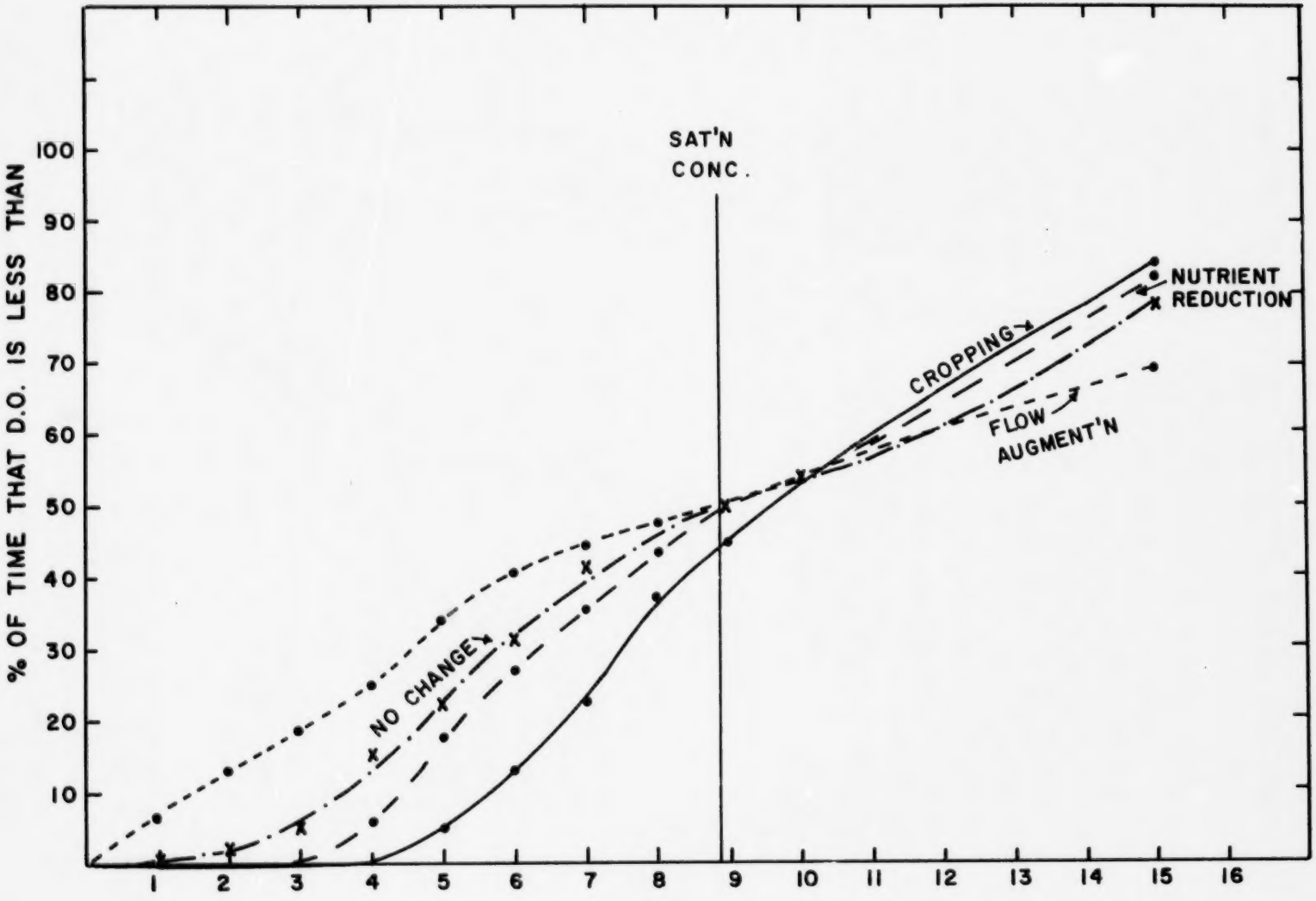


FIGURE 42 DISSOLVED OXYGEN CONCENTRATION DISTRIBUTIONS FROM SIMULATION OF MANAGEMENT SCENARIOS.

about 6% of the simulation period. Flow augmentation and the subsequent steady nutrient supply resulted in a violation of the 4 mg/L level about 25% of the time.

These similations are not intended as actual predictions of expected conditions under various imposed scenarios. It is unlikely that nutrient reduction would lead to a one third reduction in filterable phosphorus in the stream at all times and flow augmentation would not necessarily result in the high nutrient flux used in these examples. They are meant to illustrate the types of schemes that can be tested with this model and to indicate the relative sensitivity of the model to various changes. It was obvious from the flow augmentation example that the positive growth potential resulting from additional nutrient supplied far outweighed the opposite effect of deeper flow and more dilution. Management scenarios must be screened before simulation, and traditional thinking regarding the oxygen dynamics of rivers must be re-evaluated when dealing with shallow streams.

7. RESULTS AND DISCUSSION

An aquatic plant model was developed from field and laboratory data for use in the Grand River study. The model was used to simulate seasonal biomass density trends on the central Grand and Speed Rivers, and short time scale (2 hr.) assimilation of oxygen, nitrogen and phosphorus. The model ECOL1 was then incorporated into dynamic and pseudo-steady state models as a subroutine.

Model calibration was successfully carried out using detailed monitoring data from the Grand River upstream of Breslau. Observed seasonal biomass trends were duplicated by the model within the confidence limits of observed densities. Short term fluctuations (1-2 hr) in oxygen concentration can be predicted within acceptable limits.

Verification of the model was also successful when data from the Speed River downstream of Guelph were used. Larger errors in comparison to those for the calibration reach resulted for the prediction of daily maximum dissolved oxygen, and it was felt that

some of this error was attributable to other respiratory processes in the stream (NOD, BOD); and some difficulty was also encountered in predicting reaeration rates. The seasonal trends in biomass were modelled satisfactorily.

The model is useful as a river basin management tool either independently, as part of general dynamic water quality models and/or as part of pseudo-steady state models. The model is sensitive to fluctuations in environmental factors in a given reach (temperature, solar radiation, available phosphorus). It can therefore indicate the sum of returns realized by such stream management options as flow augmentation, channelization, water removal or addition of water at a point, changes in quality or quantity of sewage effluent, non-point source control of suspended solids and nutrients, instream remedial measures, and stream bank alterations. The plant community is a very dynamic community and generally will be altered by any significant change in the system's chemical or physical nature.

The model is limited in time and space and care must be exercised in applying it in environments different from that in which it has been tested and applied. Considerations have not been made of pH and therefore the model must be used in hardwater streams with pH > 7.0 and containing suitable hard calcareous substrates. As well, stream velocity must be sufficiently high (> 0.3 m/s) to favour the growth of algae and plants involved. This model is limited to modelling the three types of aquatic plants discussed, namely Cladophora, P. pectinatus and periphyton.

The model has not been tested using the pre-June or post-September data and therefore cannot be recommended for use during these periods without further testing. At present, typical June 1st initial conditions must be input to the model. Severe storms or extreme weather conditions have not been modelled to determine their effects on the plant community, and it is not known whether the model would behave realistically under such extremes.

Best results are achieved with this model on reaches which display a high degree of morphometric homogeneity, since average reach parameters are used throughout. Deep pools in reaches will tend to bias model results. A short time step (1-2 hrs) is also desirable since solar radiation induced changes in a weed bed are very rapid. This is not a model limitation but rather a fact of metabolism in overabundant plant communities. Likewise, short reaches (< 3 hrs. time of travel) are also desirable for similar reasons.

Some of the submodels involved require additional calibration to improve the model's universality and predictive capabilities. The effect of these submodels is sometimes difficult to isolate from a particular algorithm and further calibration will require detailed and specialized measurement and experimentation. Areas in the model which require additional refinement are the temperature models for productivity and washout, self-shading, effects of low oxygen concentration on respiration, rates of luxuriant phosphorus uptake and utilization of stored phosphorus and the efficiency of utilization of available nutrients by plants. Approximate accounts are made of these relationships in the model and a degree of success has been achieved, yet further research into these factors would not only improve the model, but also add to the knowledge accumulated to date regarding instream processes in shallow water. It is the recommendation of these authors that this model be used with care, that its predictions be interpreted with the understanding of its limitations.

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APPENDIX

Although designed and developed specifically for the Grand River, ECOL1 has the potential for application to a variety of riverine systems. Subsequent to the work described in this report, ECOL1 was applied to a neighbouring river in a different watershed. Several problems were encountered in achieving successful calibration during that application. Project staff believed that empirical relationships developed for the Grand and Speed Rivers work, although excellent for those systems, were difficult to transfer to other river basins. An effort was therefore made to reprogram ECOL1 in a manner consistent with available theory rather than empirical observations, in the hope that such coding would be more generally applicable.

The revised version was called ECOL2 and was in fact more easily calibrated for the new river systems than was ECOL1. The changes incorporated into ECOL2 are outlined below

1) New equations to determine the amount of solar radiation back-reflected under varying cloud covers were taken from Hutchinson (1975)
   where $BF = 0.20 * ANGLE^{(-0.30)}$
   under a bright sunny sky
   $BF = 1.18 * ANGLE^{(-0.77)}$
   under a moderate cloud cover
   $BF = 0.78 * ANGLE^{(-0.68)}$
   under heavy overcast
   BF = back reflection
   ANGLE = solar altitude
2) Use of the equations shown in 1 above required the calculation of solar altitude by
   $ANGLE = 90 - 2A$
   where 2A = zenith angle of the sun
   The zenith angle is the angle calculated by the AES model (WON 1978)
3) Although it is not clear in the text of this report, the equations to determine the amount of species specific light limitation follow Michaelis-Menten kinetics, with the model constants IC, IP, IE representing Michaelis-Menten half-saturation constants for light.

4) A phosphorus bioavailability factor was added to the volumetric phosphorus availability equation to account for the difference between total phosphorus (i.e. particulate and soluble phosphorus) as input and that fraction of the total which it is possible for plants to utilize (usually most of the soluble and a small amount of the particulate phosphorus).
5) The oxygen dependency term in the species specific respiration equations was changed to reflect Michaelis-Menten kinetics with the half-saturation constant for oxygen being set to 1.5.

It should be noted that the constants in the equation for reaeration (K2) in the ASSIM subroutine are not programmed as input variables. Before applying the model to another river system, the user should make the appropriate modifications to the program code to enable the model to calculate correct values for K2. No attempt was made to repeat the calibration of ECOL2 for the Grand River since the empirical relationships employed in ECOL1 worked well for that system, as demonstrated by the excellent calibration results obtained (p. this report). It is anticipated that good calibration could also be obtained with ECOL2 although calibration coefficients for the two model versions could take different values

POOR

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